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JOHNSON ENGINEERING CORPORATION

FINAL TEST REPORT FOR THE UNISTIK™ VEHICLE CONTROLLER

CONTRACT NAS 9-16189

MARCH 1988

FINAL TEST REPORT

FOR THE

UNISTIK^{TM} VEHICLE CONTROLLER

CONTRACT NAS 9-16189

MARCH 1988

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FOREWORD

This Final Test Report is submitted by Johnson Engineering Corporation to the National Aeronautics and Space Administration (NASA) in accordance with Paragraph 4.17.2 of the Statement of Work included in Modification 19C, dated May 19, 1986 to Contract NAS 9-16189, UNISTIK™ Vehicle Controller.

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Section 1

INTRODUCTION

The purpose of this report is to summarize the results of the testing of the UNISTIK™ Preproduction Prototype Unit (PPU) during the testing portion of Phase II. Included in the body of this report is a summary of the results of the road testing, bench testing, and the Vancouver, British Columbia, road trip results, as well as a discussion on system reliability, and problems encountered during the testing.

The final section of the report addresses conclusions drawn from Phase II of this project.

More detailed discussions of individual test results are included as Appendix C.

Section 2

SYSTEM DESCRIPTION

The UNISTIK™ is fully described in "Technical Documentation for the UNISTIK™ Vehicle Controller", Section 2, and the Final Report, Section 4.

Section 3

TEST PROGRAM

3.1 TEST PROGRAM SYNOPSIS

There are two major portions of the UNISTIK™ Phase II test program: road tests and bench tests. A subcategory of the road tests was the testing accomplished during the Vancouver trip where the UNISTIK™ vehicle was displayed at EXPO '86.

Detailed descriptions of each of the two major test categories are provided in the road (driving) test plan which is attached to this report as Appendix A, and the bench test plan which is attached as Appendix B.

In summary, the road tests consisted of the tests listed in Table 3-1. As noted from this table of tests which were performed while driving the UNISTIK™ vehicle, the UNISTIK™ system was tested at both low speeds and highway speeds. The systems were operated normally when simulated faults occurred with the system. Additionally, the system was tested for its ability to perform if vehicle failures occurred, such as loss of power steering or brakes, and with occurrence of a flat tire.

The bench tests consisted of temperature testing of the electronics of the steering servo system (the most complex of the servos in the system) and a mechanical cycle test for the steering and brake servo systems to determine wear characteristics of the mechanics of the system.

The following subsections summarize the results of all tests performed on the UNISTIK™ system during Phase II. Detailed descriptions of key aspects of each test result are contained in Appendix C.

3.2 ROAD TEST RESULTS SUMMARY

3.2.1 Normal Operation

The UNISTIK™ accelerator performs the same as manual vehicle control. The brakes were given extra sensitivity to enable rapid stops. Training is necessary before drivers become accustomed to the feel of the system to the point where they can brake smoothly.

TABLE 3-1. LIST OF ROAD TESTS IN ROAD TEST PLAN

SYSTEM NORMAL - FUNCTIONAL TESTS

LOW SPEED TESTS	HIGH SPEED TESTS
ACCELERATION/DECELERATION	ACCELERATION/DECELERATION
STRAIGHT LINE BACKUP	LANE CHANGING
RIGHT ANGLE PARKING	TIRE ON SHOULDER
TURNABOUT	EMERGENCY STOP
PARALLEL PARKING	OBSTACLE AVOIDANCE
SLALOM COURSE	
EMERGENCY STOP	
OBSTACLE AVOIDANCE	

VEHICLE FAILURE - RESPONSE TESTS (LOW SPEED)

POWER BRAKE LOSS	POWER STEERING LOSS	FLAT TIRE (FRONT)
DECELERATION	SLALOM COURSE	ACCELERATION/DECELERATION
EMERGENCY STOP		SLALOM COURSE

UNISTIK™ SYSTEM FAILURE - RESPONSE TESTS

LOW SPEED TESTS	HIGH SPEED TESTS
SLALOM COURSE (STEERING)	LANE MAINTENANCE (STEERING)
POWER AMPLIFIER POWER LOSS	POWER AMPLIFIER POWER LOSS
POWER AMPLIFIER COMMAND FAILURE	POWER AMPLIFIER COMMAND FAILURE
POWER AMPLIFIER COMMAND OFFSET FAIL.	POWER AMPLIFIER COMMAND OFFSET FAIL
JOYSTICK SIGNAL FAILURE	JOYSTICK SIGNAL FAILURE
POSITION FEEDBACK SIGNAL FAILURE	POSITION FEEDBACK SIGNAL FAILURE
TACHOMETER SIGNAL FAILURE	TACHOMETER SIGNAL FAILURE
MICROPROCESSOR WATCHDOG FAILURE	
	LANE CHANGING (STEERING)
DECELERATION (BRAKE)	POWER AMPLIFIER POWER LOSS
POWER AMPLIFIER POWER LOSS	POWER AMPLIFIER COMMAND FAILURE
POWER AMPLIFIER COMMAND FAILURE	POWER AMPLIFIER COMMAND OFFSET FAIL
BRAKE/THROTTLE JOYSTICK SIGNAL FAIL.	JOYSTICK SIGNAL FAILURE
	POSITION FEEDBACK SIGNAL FAILURE
EMERGENCY STOP (BRAKE)	TACHOMETER SIGNAL FAILURE
POWER AMPLIFIER POWER LOSS	DECELERATION (BRAKE)
POWER AMPLIFIER COMMAND FAILURE	POWER AMPLIFIER POWER LOSS
BRAKE/THROTTLE JOYSTICK SIGNAL FAIL.	POWER AMPLIFIER COMMAND FAILURE
	BRAKE/THROTTLE JOYSTICK SIGNAL FAIL

The slalom course maneuvers showed an interesting result. As each of three test runs was made, there was improvement in performance for each driving method. This indicates the learning and familiarization achieved. A comparison of the slalom performance for the third try through the course for each driving mode was informative.

When driving with UNISTIK™ the third time through the course, the time was 40% faster than the first try. The improvement from first to third try was only 16% for manual control. The difference between manual and UNISTIK™ modes of driving on the third try was an average of 16.5% (UNISTIK™ being faster). Faster speeds were observed when driving with UNISTIK™; higher lateral accelerations were experienced; and the time between steering motion peaks was better. A major reason for this result is that steering is so much easier with the joystick, especially maneuvers requiring large rotations of the steering wheel.

With practice similar improvement and overall better performance from the UNISTIK™ system was also observed in obstacle avoidance maneuvers.

In emergency stopping maneuvers both control systems appear to perform in the same manner. UNISTIK™ is fully capable of performing emergency stopping maneuvers as quickly as with the manual mode of driving.

Once the driver has had sufficient time to practice and develop experience, driving with the UNISTIK™ system at highway speeds was comparable with manual driving. It is estimated that 30 to 60 minutes is all that is required to gain experience at highway speeds with the UNISTIK™ driving mode.

Maneuvers such as lane changing, driving with one tire on the shoulder of the road, or obstacle avoidance resulted in similar control characteristics for the two driving modes. The only noticeable difference while driving with UNISTIK™ was a slight overcorrection tendency when exiting a maneuver. This overcorrection tendency caused no significant driver problem in control of the vehicle and was, in general, not noticeable by passengers. Accelerometers were the only indicator of overcorrection tendency.

Once experience was gained in using the UNISTIK™ system the driver could comfortably drive with the UNISTIK™ system on typical highways and in traffic situations.

3.2.2 Simulated Vehicle Malfunctions

Because of the results of the low speed vehicle malfunction tests no high speed vehicle malfunction tests were performed. During the low speed tests in this series, three vehicle malfunctions were evaluated: power brake loss, power steering loss, and flat front tire.

When the vehicle power brake vacuum was lost, the UNISTIK™ brake servo successfully brought the vehicle to a stop, although it took approximately twice the distance. The servo exerts more force than the typical driver can exert, so the braking distance compares favorably with manual driving.

Similarly, the steering system could control vehicle direction when the engine was shut off, although it was much more sluggish. The system exerts more force on the steering wheel ~~then~~ than the typical driver can exert, so UNISTIK™ performs at least as well as manual driving in such a situation.

When a front tire was purposely flattened to test the UNISTIK™ response to such a vehicle problem, there was no apparent difference in performance driving with UNISTIK™ compared to driving manually. The steering was not impaired by the extra drag caused by the flat tire.

3.2.3 Simulated UNISTIK™ System Malfunction

For this series of tests, fault signals were introduced in joystick, feedback and tachometer signal inputs to the steering servo electronics. Faults were also introduced into the input to the power amplifier, and into the low level circuit operational amplifier circuitry. Similar faults were introduced into the brake servo electronics. Feedback and tachometer signals are not used in the brake servo.

Since the steering and brake servo systems are the most critical functions for controlling the vehicle, faults were introduced only into these systems. Through brake/throttle joystick fault signals, the throttle malfunction condition was also evaluated.

3.2.3.1 Steering Servo System Malfunction Tests

When the various fault types were introduced into the UNISTIK™ steering servo electronics during a low speed slalom course maneuver, the following results were seen: Depending on the steering conditions when the fault occurred, the time of fault introduction, and the type of fault introduced, the results varied from no steering wheel rotation to a maximum of 10 degrees of wheel rotation. The time required for the system to detect the fault and switch to the secondary steering servo system varied from 0.1 to 0.5 seconds. The condition which caused the worst case 10 degree steering wheel movement before the secondary circuit switched into operation was a 12 volt DC voltage fault at the power amplifier command line. This 10 degree rotation required minor corrective action by the driver to control direction of travel after the secondary system was switched in. All other faults created 5 degree or less rotations and, for the most part, no steering corrections by the driver. This means that even the worst case fault did not cause loss of vehicle control.

The magnitude of effect on the steering wheel position, when the faults were introduced, were principally related to two factors: the difference between the fault signal value and the value of the actual signal just prior to introduction of the fault, and the length of time between fault introduction and switchover to the secondary servo electronics. The greater the difference in voltage levels and the greater the time delay, the more effect on the steering wheel motion.

The lane maintenance tests at 40 and 55 miles per hour produced similar results to the low speed slalom tests. Most faults, when switched into the system, created very small or negligible perturbations in the steering wheel rotation. It was apparent that when the vehicle is traveling straight, there is a tendency for faults not to cause large perturbation in the steering.

One interesting result of the tests was that with identical faults and nearly identical signal levels in the servo electronics prior to fault introduction, different delay times were observed between the time of fault introduction and secondary servo electronics switch-in. Depending on where the microprocessor is in its multitasking software operation, apparently caused the result. A significantly different time is involved in detecting hardware signal faults and taking action on that decision. In the case observed with all other parameters nearly identical during this test series, the time difference was 0.1 seconds and 0.25 seconds. In worst case observed, this varying time for system response caused the driver no problems in getting the vehicle under control again. The steering wheel rotated about 15 degrees for the longer time and required only minor compensation corrections by the driver.

For lane change maneuver tests, steering maneuvers were in process when the fault was introduced. In these tests, more reaction was observed due to some of the fault types introduced into the signal paths. Out of the twenty-five tests performed, including both 40 and 55 miles per hour, seventeen caused negligible or only very slight steering wheel motion between the time the fault was introduced and the time of switch-in of the secondary circuit. The remaining eight tests resulted in steering wheel rotations of 10 to 30 degrees. These eight cases required only small corrective action by the driver during the time between fault introduction and secondary circuit switch-in.

Steering servo fault introduction at both low and high speeds created no uncontrollable situations for the driver. In fact, in most cases, the fault introduction and switchover process was barely perceptible. The first series tests were due to system problems which have since been corrected and new tests performed verifying correct performance.

3.2.3.2 Braking Servo System Malfunction Tests

General reactions of the UNISTIK™ braking system to fault voltage introduction into the power amplifier command line was predictable. They depended on the value of the fault voltage relative to the actual command line signal prior to fault introduction. A 5 volt signal represents no applied brake. If the voltage was greater than 5 volts, and also greater than the existing brake command signal at time of fault introduction, the brakes would be applied harder when the fault was introduced. If the fault voltage was lower than the existing command signal, the brakes would be released when the fault was introduced.

Table 3-2 summarizes the critical data results from the second series of brake servo system malfunction tests wherein a fault was simulated in the brake power amplifier command line. The first test series resulted in unacceptable data. Software and hardware changes were made before the second test series were performed.

TABLE 3-2. TIME TO RE-APPLY BRAKES TO ORIGINAL LEVEL AFTER BRAKE COMMAND FAULT INTRODUCTION (SECONDS).

BRAKE COMMAND FAULT	DECELERATION FROM 30 mph (sec.)	40 mph (sec.)	55 mp (sec.)	EMERGENCY STOP FROM 30 mph (sec.)
Pwr Loss	1.1	.4	.4	.2
5 volt	1.2	2.7(a)	1.5(a)	.6
3 volt	.45	.45	.5	.65
7 volt	1.5	.5	.5	- (b)
0 volt	.4	.5	.3	.65
12 volt	.1	.1	.4	.15

Notes (a) Eventually, the fault was detected, but further joystick motion was required to allow detection. Deceleration did continue during interim period.

(b) The fault signal did not create large enough error to allow fault detection, until after stop completed and the throttle pressed again. Deceleration was completed, however.

From Table 3-2, for a given fault condition, some variation in fault detection times exist. This is similar to the results observed with simulated steering servo faults. It is apparent that most faults were detected, secondary switch-in accomplished, and the brake control returned to its pre-fault condition in less than one second.

Two fault conditions had some difficulty being detected. These were 5 volt and 7 volt fault voltages on the command line. The reason for this is that the actual command signal prior to the fault introduction was in a range near 6 volts. Both the 5 or 7 volt faults were fairly near the correct voltage and, in most cases, were not detected until further joystick motion increased the magnitude of the error between the fault and the expected voltage.

In the case of the 5 volt fault some minor deceleration was possible, even while the fault was engaged and before the secondary circuit was switched into operation. Since the vehicle did not respond as the driver intended, the natural tendency was to apply more braking by further joystick. This motion caused an increased error signal which could then be detected by the monitoring microprocessor. This reaction created the long detection times observed during deceleration for 5 volt fault signals. The deceleration did continue during the fault period.

The 7 volt fault signal is higher than the pre-fault voltage and the brakes were applied harder when the fault was introduced. In some cases of this fault, the vehicle was stopped faster than desired but the vehicle did stop. In the emergency stop case, the failure of the system to detect the fault until the next time the throttle was pressed does not pose a serious safety problem. The vehicle stopped in the same distance as a normal (no-fault) emergency stop maneuver.

The delays resulting in the majority of the fault detection conditions still allowed the vehicle to be stopped in the planned distance. In spite of the momentary release or harder application of the brakes, the driver could compensate during the remainder of the deceleration maneuver. In the emergency stop maneuvers and if the fault was in a direction to release the brake, the delays of up to 0.65 seconds would result in extra stopping distance in the emergency situation. In the worst delay seen (0.65 seconds), the test results for the emergency stop from 30 miles per hour would have caused the emergency stop maneuver to take less than 29 feet more distance.

Table 3-3 summarizes the results of faults introduced into the brake/throttle joystick signal line.

TABLE 3-3. TIME TO RE-APPLY BRAKES TO ORIGINAL LEVEL AFTER BRAKE/THROTTLE JOYSTICK FAULT INTRODUCTION (SECONDS).

BRAKE JOYSTICK FAULT	DECELERATION FROM 30 mph (sec.)	DECELERATION FROM 40 mph (sec.)	DECELERATION FROM 5mph (sec.)	EMERGENCY STOP FROM 30 mph (sec.)
0 volts	.4(a)	.4(a)	.4(a)	.3(a)
12 volts	.1	.05	.05	.1
open ckt	.5(a)	.4(a)	.35(a)	.3(a)

Notes (a) Throttle was disabled as quickly as the brake secondary was switched in.

The results of the brake/throttle joystick signal fault simulation were similar to the results when the command signal faults were simulated. The 0 volts and open circuit faults resulted in fault detection, secondary switch-in, and re-application of brakes to pre-fault levels in 0.3 to 0.45 seconds. This type of fault created a situation, until the fault detection was completed and the secondary brake servo electronics switched into operation, where the brakes were released and the throttle applied. During the same period, the throttle activation was detected and subsequently shut off by the monitoring microprocessor.

The 12 volt fault on the joystick signal line applied a signal in the same direction and in greater magnitude to normal brake application. The results did cause faster, jerky braking until the vehicle stopped.

3.2.3.3 Conclusions of System Malfunction Simulation Tests

The result of all the UNISTIK™ system malfunction simulation tests is that there were no reactions from the system that caused excessive driver reactions. Situations were not created which caused the vehicle to become uncontrollable in any manner dissimilar to the response of the vehicle when driven manually. Problems which occurred during the first series of tests were corrected by hardware and software modifications. These modifications were completed prior to retesting for the "problem" fault conditions.

3.2.4 Vancouver Road Trip Results

Eight driving days were spent driving the UNISTIK™ vehicle from Boulder, Colorado to Vancouver, British Columbia, Canada, and return. A total of 3521 miles were driven during the trip, of which 3398 miles were driven with the UNISTIK™ system. The manually driven miles were, for the most part, in Canada where the UNISTIK™ system was not used on public roads. Only 17 total miles were driven manually within the United States portion of the trip, on very short trips between motels and restaurants where it was not practical to load the UNISTIK™ software from the disk drive. (It is no longer necessary to load the software before driving, since it is resident in hardware).

Data gathered during the trip, in the form of chart recordings and engineering notes, documented the performance of the UNISTIK™ system and recorded information on the driving characteristics of the system.

Problems and comments related to the test drive portion of the trip are summarized in the following paragraph. While on display at the EXPO '86, two hardware faults occurred during the system demonstrations. These are discussed in Section 4.

3.2.4.1 UNISTIK™ Performance Problems Exhibited During EXPO '86 Trip

Further testing of the system showed that these errors were caused by the processor power supply. A different supply was designed, which eliminated all false alarms.

The problem incidents 3 and 6 from Table 3-4 were caused by friction in the brake pedal servo drive system which occasionally prevented the brake pedal return spring from fully releasing the pedal after it had been pressed. There were no repeats of this incident on the return trip. The removal and reinstallation of the brake servo mechanism and adjustment of the mechanisms allowed the brake pedal to return to its fully released position.

Because the steering wheel showed some vibration during the incident, the buzzing noise heard from the servomechanisms (incident number 14) appeared to be in the steering servo system. No hardware fault has been found to justify such a reaction from the system. It is important to note that the steering

TABLE 3-4. PROBLEMS ENCOUNTERED DURING VANCOUVER ROAD TRIP

DAY	NO.	MESSAGE OR CONDITION	CIRCUMSTANCES	ACTION TAKEN	RESULTS
1	1	"PULL BACK JOYSTICK"	LEAVING FREEWAY/TERMINAL HOOKUP	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	2	"SECONDARY STEERING POSITION ERROR"	AIR CONDITIONER FROZE	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	3	BRAKE LIGHT CAME ON AFTER SYSTEM SHUT OFF	WHEN LEFT PARKED	PULLED BACK PEDAL	LIGHT WENT OFF
2	4	"SECONDARY STEERING POSITION ERROR"	FREEWAY DRIVING AFTER STARTUP	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	5	"STEERING WARNING" & "SYSTEM FAILURE"	DOING TURNABOUT	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	6	BRAKE LIGHT CAME ON AFTER SYSTEM SHUT OFF	WHEN LEFT PARKED	PULLED BACK PEDAL	LIGHT WENT OFF
	7	"SECONDARY STEERING POSITION ERROR"	FREEWAY DRIVING AFTER STARTUP	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	8	"SECONDARY STEERING POSITION ERROR"	FREEWAY DRIVING	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
3	9	"SECONDARY STEERING POSITION ERROR"	FREEWAY DRIVING AFTER STARTUP	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	10	"SYSTEM FAILURE"	AFTER INVERTER TURNED OFF	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	11	"SECONDARY STEERING POSITION ERROR"	FREEWAY DRIVING AFTER STARTUP	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	12	"SECONDARY STEERING POSITION ERROR"	FREEWAY DRIVING AFTER STARTUP	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	13	"SECONDARY STEERING POSITION ERROR"	FREEWAY DRIVING AFTER STARTUP	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	14	BUZZING NOISE IN SERVOMECHANISM	WINDING, HILLY ROAD, LOW SPEED	NONE	BUZZING STOPPED(2 SEC)
4		NONE			
5		NONE			
6		NONE			
		NONE			
7	15	"SYSTEM FAILURE"	HIGHWAY DRIVING	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	16	"SYSTEM FAILURE"	HIGHWAY DRIVING	RESTARTED SYSTEM	BUZZ SOUND,NEW FAULT
	17	"PRIMARY STEERING POSITION ERROR" & "SYSTEM FAILURE"	FEW SECONDS AFTER PREVIOUS MESSAGES	RESTARTED SYSTEM	NO REPEAT OF MESSAGES
	18	"SYSTEM FAILURE"	LEAVING HIGHWAY	RESTARTED SYSTEM	NO REPEAT OF MESSAGE
	19	"SYSTEM FAILURE" & THROTTLE DISENGAGED	LEAVING PARKING SPACE	RESTARTED SYSTEM	NO REPEAT OF OCCURRENCE
	20	"SYSTEM FAILURE" & "THROTTLE SERVO ERROR"	STARTING TO DRIVE, WITH PARK BRAKE RELEASING	RESTARTED SYSTEM	NO REPEAT OF MESSAGES
8		NONE			

servo system continued to function during this incident. Steering maneuvers were being accomplished during the time it was happening. Once the main control switch has been placed in the run position this type of problem can not have been caused by software. The microprocessor is removed by relay contacts from any direct connection to the servo systems.

None of the incidents created a dangerous, uncontrolled situation with the vehicle. In all cases, the vehicle remained under the control of the driver. The UNISTIK™ system continued to function under all conditions.

3.2.4.2 Other Information Gained During the Road Test

The UNISTIK™ system was used to drive the vehicle on many types of roads, including freeways, two lane highways, mountain pass roads, winding roads, and rough gravel roads. The vehicle was driven in rainstorms and during windy conditions. Isolated roads and heavy traffic situations were encountered during the trip. In all cases, the UNISTIK™ system was easy to use and there were no problems driving under these varied conditions. Ambient temperatures from 38 degrees to 85 degrees Fahrenheit were experienced with no noticeable effects during the trip.

There was a small amount of left bias required for the vehicle to be driven straight. This was caused partly by a slight misalignment of the vehicle mechanical steering. The remainder was due to crosswinds.

It was more difficult to maintain proper lane travel when crosswinds were present. This would also have been the case if driving manually. The chart recordings show up to 33.5% joystick motions (cyclic in nature) while driving in crosswind conditions. On a day without such crosswinds, the joystick motion was reduced to about 14% peak.

During the earlier part of the trip, there was a strong tendency for the driver to make very rapid (less than one cycle per second), small magnitude (less than 5%) corrections in the steering. With experience these small corrections tended to be less prevalent. Toward the end of the trip and regardless of driving conditions, the steering motions changed character significantly and tended to vary widely, in level and frequency, indicating reaction to actual conditions rather than a continual cyclical correction.

Even though the joystick excursions were up to 33% occasionally, the non-linear steering response meant that only about 10 degree steering wheel motions were observed for normal steering corrections.

In general, more concentration was required to drive by joystick, rather than manually, due to the sensitivity of the joystick controls. This extra concentration was not overly fatiguing. Two to three hour driving sessions did not create excessive fatigue.

It is apparent from the video recordings taken during the trip that there was a tendency for the vehicle to move slightly back and forth within its driving lane as steering corrections were made by the drivers. This is also normal in manual driving situations. At the end of the trip, the hardware, both mechanical and electrical, was inspected. A broken solder joint on one indicator lamp in the transmission gear selection panel was found. There was some wear on the steering wheel base where it had rubbed against the servomechanism cover. This was the only evidence found of any mechanical vibration or wear occurrence during the trip. No wear was evident on any gearing.

3.2.4.3 Conclusion of Vancouver Road Trip Test

The UNISTIK™ system performed during the entire 3398 miles without any repairs required, or major delays, and the system was easy to use. The drivers quickly became comfortable with its use in all road conditions.

3.2.5 Comparison Between Able-Bodied and Disabled Drivers

A brief road test of driving ability for a C5 Quadriplegic was performed and compared with data taken with able-bodied drivers with limited UNISTIK™ driving experience. The results were very comparable. The steering joystick motions were of similar magnitude and frequency after about 15 minutes of driving experience. The same hesitancy existed for the first few minutes as the drivers became accustomed to the new driving methods. The disabled driver had limited use of only one hand, and hence had a problem with activating the manual secondary controls. This was especially true of the turn signals which were needed on a regular basis while driving. The passenger had to activate the turn signals for the handicapped driver. Voice activated controls required in a production version of the UNISTIK™ system would eliminate this problem. The disabled driver gained confidence during the relatively short driving experience of about 15 minutes. He drove the vehicle to speeds of approximately 40 miles per hour. The handicapped driver had used the UNISTIK™ system previously, but a considerable time interval had elapsed since the previous use. The previous use had been at lower speeds mostly in confined parking lot areas.

3.3 BENCH/LABORATORY TEST RESULTS SUMMARY

3.3.1 Test Fixtures/Test Setup

The test plan for the bench/laboratory tests is included as Appendix C in this report. A test fixture was provided for the temperature cycle and extended temperature test portion of these tests. Both of these temperature tests utilized the same test fixture. Figure 3-1 shows a block diagram of the test fixture and steering servo electronics which were set up to perform the tests. Appendix C contains a more detailed discussion of the bench tests results and sample data recordings.

A specially designed signal generator provided signals to simulate the steering joystick signal, steering position feedback signal, the steering tachometer signal, and the vehicle speed signal. The steering feedback signal varied in magnitude as a function of the vehicle speed signal. These signals are shown in Figures C-132 and C-133 of Appendix C.

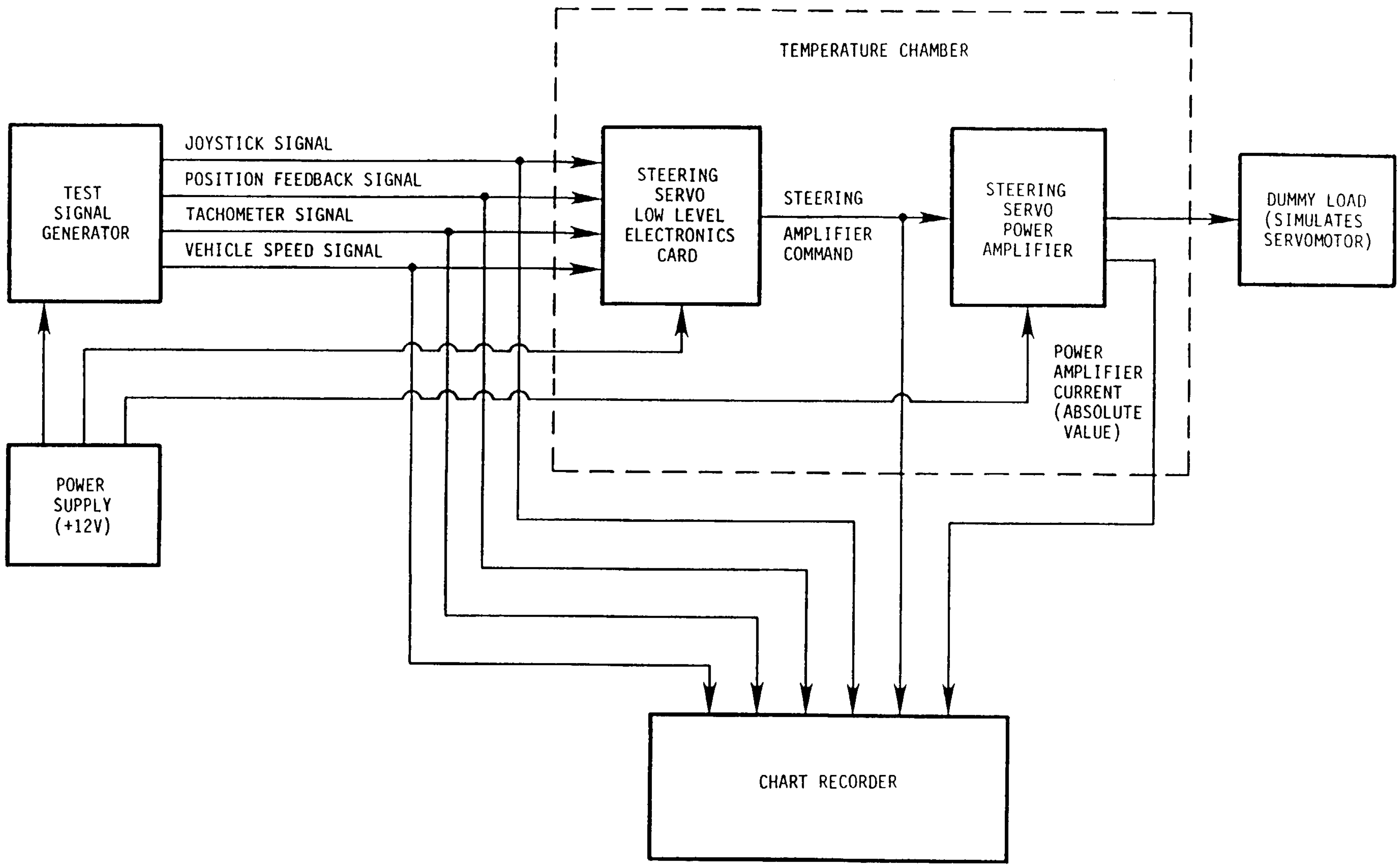


FIGURE 3-1. BENCH TEST EQUIPMENT BLOCK DIAGRAM

For the mechanical cycling test, a special program adaptation of the basic UNISTIK™ software was written to provide continuous cycling of the steering servos from one end of their travel to the other and to press the brake pedal in a similar cyclical fashion. To provide performance evaluations, the software monitored the steering and brake functions and stored data on their movements in battery backed RAM memory in the microprocessor circuit. If incorrect performance was detected, the system would stop cycling. If any problem developed, the data collected and the system condition was used to determine the cause.

The front of the vehicle was jacked up a proper amount to allow sufficient drag on the steering to simulate typical loads on the steering servo that would be present when the vehicle was running and the power steering operational. This allowed the test to be performed without the vehicle engine running.

3.3.2 Steering Servo Electronics Temperature Cycle Test Results

The steering servo electronics were cycled twice, from -40°C to +80°C, with no problems in performance observed. The power amplifier was operated without any problems and without the benefit of a cooling fan during these tests. During times when the ambient chamber temperature was stabilized, the heat sink temperature was less than 10 degrees higher than the chamber temperature.

At each extreme end of the temperature range and at room temperature, the performance of the servo electronics was tested at three different power supply voltages (10.6 volts, 12 volts, and 13.4 volts). Details of the results of the temperature cycle tests are shown in Appendix C. The results are summarized in Table 3-5. The principle changes observed during the tests were changes in the center reference voltage in the power amplifier compared to the power supply voltage and temperature and changes in the low level circuit gain compared to the temperature. These data are shown in Table 3-5.

TABLE 3-5. TEMPERATURE CYCLE TEST RESULT SUMMARY DATA

	Power Amplifier Center Reference Voltage Change vs Supply Voltage			Low Level Circuit Gain Change
Chamber Temperature	10.6 volts	12 volts	13.4 volts	12 volts(1)
+80°C	-10%	0%	+5%	+15%
+25°C	-19%	REF	-1%	REF
-40°C	-29%	0%	0%	-6%

Note (1): Gain did not change as function of supply voltage.

It can be seen from Table 3-5 that the largest changes in the power amplifier center reference voltage, indicating the center of the steering position, occurred at the 10.6 volt power supply voltage. This operating voltage also resulted in the largest variation with temperature. The reason for this is that the voltage regulator diodes did not receive sufficient current at that low of supply voltage to remain in their regulating region. This, in turn, allowed voltage reference levels to vary, causing the results seen.

The 12 and 13.4 volt results are more representitive of the range of supply voltage variations expected in normal operating conditions. In these cases, the worst variation was 5% observed at the highest supply voltage and the +80°C temperature. All data shown are compared to the 12 volt supply at a +25°C temperature value.

Since the gains were essentially determined by resistor values in the operational amplifier circuits, there was no measurable effect on the low level circuit gains due to power supply voltage changes. Temperature did have some effect, shown in the last column of data in Table 3-5. Compared to the gain at +25°C, the gain increased 15% at the +80°C temperature and decreased 6% at the -40°C temperature.

The changes observed in the power amplifier center reference voltage would affect the steering position for center joystick position. Changes in this steering position could be easily compensated by joystick position changes and would have only a minor effect on the drivability of the UNISTIK™ system under such extreme conditions. The effect would be similar to the joystick offset experienced during the Vancouver trip due to the slight steering misalignment condition.

The gain changes measured during this test would probably not be noticeable to someone driving with the UNISTIK™ system. The joystick travel required for a given magnitude of steering maneuver would change only a minor amount. During full lock-to-lock steering maneuvers used occasionally in parking, the changes would be noticeable and this only at the -40°C condition.

The results of this test indicated that the performance of the steering servo electronics when driving with the UNISTIK™ system, under temperature and voltage variations, was acceptable for normal driving conditions.

3.3.3 Servo Electronics Extended Temperature Test Results

The same set of steering servo electronics was used for the extended temperature test. The electronics were subjected to continuous +60°C temperature for 168 hours. The electronics power supply was cycled on and off for five of the seven test days. During this period a total of approximately 45 hours of operating time was logged on the electronics.

At 52 hours into the test, one component failed. It was the +/- 15 volt DC/DC converter on the low level electronics card. This component was replaced and the test continued with no further problems.

An investigation of the cause of the failure determined that the component was only rated for +60°C operating temperature. While operating in the temperature cycle test, the component had been subjected to a maximum of +85°C in temperature. It was apparently sufficiently damaged that it failed after a portion of the extended temperature test. If operation above +60°C is expected, a higher temperature rated component should be used in production models.

All other aspects of the extended temperature test were successful. Except for the minor effects of the new converter component, operation of the system after the test was completed was the same as when the test started.

3.3.4 Mechanical Cycling Test Results

In the mechanical cycling test, the steering and brake servo systems were cycled through their maximum movement range for a total of 80 hours. The cycling effects of this operation would be roughly equivalent to 10 years of normal usage of a UNISTIK™ system. This test was fully successful. There were no failures in either the electronics or mechanical hardware during the test. Inspection of the servo mechanical subsystems in both the brake and steering mechanisms after the test showed only minimal wear on the gears and other moving parts in the system.

3.3.5 Conclusions of Bench/Laboratory Test Results

The results of the bench/laboratory tests verified that the UNISTIK™ electronics and servo mechanisms are adequately designed for the application. The possible exception to this is the increased operating temperature range on the +/- 15V DC/DC converter component.

3.4 SYSTEM RELIABILITY

3.4.1 MTBF Calculations

Because of its complexity, mean-time-between-failure calculations were made for the UNISTIK™ system using the steering servo as representative. Calculations were made based on Mil Standard 217E for the electronics and NPRD-2 for the mechanical portions. The calculations were based on a typical +25°C ambient system temperature and also based on the component count method for the electronics calculations. Because all components are operated conservatively with no parts stressed near their maximum power levels, the components count method is valid.

Using the above methods, the electronic reliability calculation is summarized in Table 3-6 for one of the two redundant sections of the steering servo electronics. The components contained in each of the redundant steering servo electronics circuits result in a failure rate of 123.289 per 10^6 hours. Each of these electronic sections has two power supply modules with failure rates of 3.964 and 2.268 per 10^6 hours, respectively. Combining these failure rates with a portion of the redundant relay contacts in the primary/secondary switchover relay results in a total failure rate per redundant section of 132.185 per 10^6 hours.

TABLE 3-6. ELECTRONIC FAILURE RATES

PART TYPE	λ(hours x 10^{+6})	n	nλ(hours^{+6})
Resistor, Metal Film	0.012 x 3 = 0.036	146	5.265
Resistor, Composition	0.011 x 3 = 0.033	23	0.759
Resistor, Wirewound	0.150 x 3 = 0.45	2	0.90
Capacitor, Polyester	0.040 x 3 = 0.12	34	4.08
Capacitor, Tantalum	0.055 x 3 = 0.165	13	2.145
Capacitor, Al Oxide	1.7 x 3 = 5.1	4	20.4
I.C., Quad. Op. Amp.	0.55 x 8 = 4.4	17	74.8
I.C., CMOS Logic	0.05 x 8 = 0.4	3	1.2
Transistor, Small Signal	0.063 x 5 = 0.315	6	1.89
Transistor, Power MOSFET	0.30 x 5 = 1.5	6	9.00
Diode	0.019 x 5 = 0.095	30	2.85
			123.289

Assuming an average of 12,000 miles driven per year at an average speed of 30 miles per hour yields 400 operating hours per year. For 400 hours of operation, the resulting reliability for each side of the electronics is 0.9485. Since there are two redundant sections, the resulting combined reliability is 0.99735.

For the mechanical components the torque motor and gear train were estimated to have a combined failure rate of 5.873 per 10^6 hours for a reliability level of 0.99765.

The total combined reliability of the total steering servo system therefore is 0.995. This includes the combination of the total electronics reliability of the redundant electronics and the non-redundant mechanical components. This reliability level is for the 400 hours of operation time or approximately 12,000 miles.

3.4.2 Redundancy Considerations

From an operational safety point of view, the steering and braking servo sub-systems of the UNISTIK™ system are the most important. For this reason, these two systems were designed to have redundant electronic circuits.

As noted in the MTBF calculations, the failure rate of the electronics for the steering servo system, excluding redundancy, was 132.185 per 10^6 hours. This is due to the quantity of components used in the electronic circuits. The servo motor and gears for the servo system have a failure rate of 5.873 per 10^6 hours. The electronics have over 20 times the failure rate of the mechanical components.

The failures which are likely to occur in the electronics cannot, in general, be detected by any inspection program in advance of the failure. During operation potential failures in the mechanical components, such as motors and gears, are much more easily detected by either visual inspection or noise levels of the components.

Both of the above reasons, coupled with overall system cost limitations, have determined the design criteria to provide redundancy for the electronic sections of the steering and brake servo systems. For a reasonable cost, the redundancy of the electronics brings the reliability of the overall electronics sub-system to the point where it closely balances the reliability of the mechanical sub-system. The electronic sub-system redundancy provides for the problem of eventual failure in the electronics. A scheduled maintenance and inspection program should prevent mechanical failure which would eventually occur if the inspection and maintenance were not performed. The combination of regular inspection/maintenance programs and the electronic redundancy will provide, essentially, complete reliability of the overall system for the handicapped driver.

To further assist in the reliability of the mechanical components, the servo motors are operated at or below 1/3 of their rated capability in torque or current levels. The gearing is conservatively designed to reduce stress on these components under actual operating conditions.

A scheduled inspection and maintenance program is also important to the overall useful operating life of the mechanical components of the UNISTIK™ system. It would be appropriate to suggest 12,000 miles, or 12 months, whichever occurs first, as a time schedule for a scheduled inspection and maintenance program. This allows for very low probability of failure between maintenance intervals and provides for lubrication and other maintenance tasks on a regular schedule.

Section 4

DESIGN LIMITATIONS IDENTIFIED DURING PHASE II AND ACTIONS TAKEN

Discussions in preceeding sections of this report identified several design limitations of the Phase II UNISTIK™ system. Other limitations were discovered during the preliminary functional and testing efforts, during the EXPO '86 display time, and at other times during which the UNISTIK™ system was being operated as part of the Phase II efforts. Many of the limitations discovered were of minor nature and were corrected at the time of discovery; others required more major efforts but were still corrected. Still others are not possible to be changed within the scope of the Phase II efforts. This latter category of limitations should be considered for correction in future efforts or when additional models of UNISTIK™ are fabricated. The following discussion describes all of the design limitations discovered and what action has been or should be taken regarding each of them. Limitations identified earlier in this report are included in this section for purposes of completeness.

4.1 MECHANICAL LIMITATIONS

4.1.1 Primary Control Joystick Centering Spring

After one of the road tests, while the UNISTIK™ system was being used, one of the springs which hold the primary control joystick in its center position broke. The broken spring was modified slightly and used again for continuation of the Phase II efforts. Before another joystick unit is purchased for any future UNISTIK™ systems, a more durable spring should be identified for use in this application.

4.1.2 System Control Switch Lock

A locking solenoid was provided as part of the UNISTIK™ system design for the system control switch. This switch turns on the UNISTIK™ system and selects manual, test or run modes, and prevents the accidental moving of the switch out of the run mode while the vehicle is being driven. During initial preliminary testing, the vehicle was kept in park for extended periods with the system operating. The locking solenoid overheated and failed. This solenoid was of an intermittent, low operating temperature type. The extended period in park with the system still on overheated it. A higher temperature rated solenoid was used to replace the original solenoid to improve its performance. To ensure correct operation, future models of UNISTIK™ should provide a space for a continuous duty cycle solenoid for this function, regardless of the length of time it is operated.

4.1.3 System Control Switch Operating Force

When handicapped drivers attempted to use the system control switch, the force required to position the switch was excessive for some of them. It was determined that a longer lever on the switch would be easier to use by many handicapped drivers. This switch lever was lengthened to reduce the switching force requirement.

4.1.4 Transmission Gear Select Switch Operation

Three limitations were discovered during Phase II with the transmission gear select switches. Occasionally they will stick in the activated position after being pressed. This prevents another gear from being selected without unsticking the originally pressed switch. This is caused by the switch cover plates that float free in the switch chamber and sometimes become bound in the chamber at an angle. No correction for this limitation is planned at this time because it rarely happens and should be acceptable for the clinical testing efforts. For all future UNISTIK™ units, improved switches will be required.

Lower force or touch activated transmission gear select switches could be provided for handicapped drivers with no muscle tone in their fingers. This will be considered in future models of UNISTIK™.

The lights used to indicate the activated switch position are not visible from the driving position. This should be corrected in future models of UNISTIK™.

4.1.5 Transmission Lock Activation Force

It was discovered during initial testing of the UNISTIK™ system that, occasionally, the transmission lock solenoid assembly would not release to allow the transmission selector to be repositioned. It was determined that the linkage did not provide enough force from the solenoid to guarantee that the lock could be pulled to the release position. The linkage was redesigned, new components fabricated, and installed to provide the additional force. Since the modification was completed the sticking problem has not recurred.

4.1.6 Transmission Lock Solenoid

The transmission lock solenoid is an intermittent duty cycle unit. During heavy usage while the system was being demonstrated at EXPO '86, the solenoid overheated and seized, preventing the lock mechanism from operating properly. The solenoid has been replaced with a higher temperature rated component to improve its reliability in the existing UNISTIK™ system. In future models, this solenoid should be replaced by a continuous duty cycle component but this will require more space than is available in the existing unit.

4.1.7 Primary Control Positioning/Size

The primary control joystick module and transmission control module were determined to be mounted too close to the driver position. This denied access to the driver position by an electric wheelchair with its joystick control in position and still allow the primary control module to be in its normal operating position. The mounting bar of the module could be positioned properly for a given driver. For the clinical testing, a flexible, adjustable method of positioning was desired. For this reason, an adjustable mounting arrangement was designed, fabricated, and installed, which allows three degrees of positioning movement for the primary controls.

It was additionally determined that a smaller joystick control module would allow positioning closer to the driver's wheelchair control. This would make the use of the UNISTIK™ joystick easier for the limited dexterity user. For this to be improved, a smaller joystick component would have to be located and incorporated in future UNISTIK™ models. The present configuration will be retained for the existing unit.

4.1.8 Joystick Activated Park Brake Switch

The primary control joystick module has a switch bar included which will activate the parking brake when the joystick is pulled all the way back for maximum braking. Once the system began to be used, the bar wore on the joystick and dropped metal shavings into the joystick mechanism. The switch activation method was redesigned to ensure proper operation without wear occurring on the joystick.

4.1.9 Park Brake Limit Switch

During the road testing and after heavy usage, one of the limit switches on the parking brake failed to activate after the parking brake had released, to shut off the parking brake servo motor. It was determined that the limit switch lever had bent slightly, causing the switch not to activate at the end of the brake travel. The lever position was re-adjusted for proper operation. Future models of the UNISTIK™ should incorporate a more secure positioning method in the park brake mechanism for the limit switch levers.

4.1.10 Brake Actuator Motion

After completion of the Phase II prototype when the brake servo system was first tested, the brake would not fully activate. This was because of limited travel in the mechanism and the action of the spring installed between the servo gears and the brake pedal. To solve this problem, the spring was removed and the servo attached firmly to the brake pedal bar.

4.1.11 Brake Servo Gear Pin

During the demonstrations at EXPO '86, a roll pin which attached the brake servo motor gear to the motor shaft sheared off. It had apparently been weakening with use and finally failed. This pin was replaced by a solid, hardened steel pin.

4.2 ELECTRICAL/ELECTRONIC LIMITATIONS

4.2.1 Multiplexer Inputs

During initial preliminary testing and optimization, the analog voltages provided to the A/D converter for the microprocessor through analog multiplexers under certain circumstances exceeded the supply voltage for the multiplexer integrated circuits. When this happened, incorrect voltage signals were generated on certain A/D converter channels and damage to the multiplexer ICs resulted. To eliminate this problem, clamp diodes were installed on those analog channels which could exceed the multiplexer supply voltage.

4.2.2 D/C to D/C Converter Rating

The 15 volt D/C to D/C converter in the low level electronics circuit of the servo electronics has an operating temperature rating of only +60°C. There is no plan to locate a higher temperature component for this UNISTIK™ prototype but future models should have a higher temperature component used when operating at higher temperatures than +60°C.

4.2.3 Manual Driving Mode

In the Phase II prototype of UNISTIK™, the MAN system control switch position was intended to be used to operate the secondary controls in the manual driving mode. In this position, the transmission gears could not be selected. A modification was made in the wiring of the system, along with the addition of a relay, to allow the transmission gears to be selected in the MAN mode.

4.2.4 System Power Supply

During engine starting and other times of heavy electrical load on the vehicle batteries, the 5 volt logic supply voltage and the 12 volt system voltage would vary and not remain stable and free of noise "glitches". This was the cause of the software faults that occurred during the road trip to Vancouver. To solve this limitation, a new power supply was designed, fabricated, and installed. Whenever the main batteries dropped in voltage, this modification provided for the emergency backup battery to take over supplying power to the low level electronics, including the 5 volt D/C to D/C converter. A new charging circuit was also developed to maintain charge on the emergency backup battery. The primary and secondary 12 volt power sources were generated by D/C to D/C converters rather than directly from the vehicle 12 volt system. These improvements eliminated any power supply voltage variations due to heavy vehicle or system current loads.

4.2.5 Message Center Readability

The alpha-numeric display in the message center is unreadable in bright sunlight conditions. The separate, illuminated incandescent lamp messages in the main message center panel are sufficiently bright. Those in the secondary message panel to the left of the driver's station are not bright enough. No changes are planned for this prototype for the message center displays, but future models should incorporate a liquid crystal display unit which can incorporate all message requirements into the single unit.

4.2.6 Message Center Message Detection

It became obvious during early testing of the Phase II prototype UNISTIK™ that when a driver is busy with driving tasks, and not looking that direction at the time they appear, messages which are displayed on the message center may be missed. An audio tone was added to warn the driver that a message is to appear on the message center. This greatly improves the driver interface.

4.2.7 Emergency Flashers

The emergency flasher function (on the turn signal lights) was incorporated into the UNISTIK™ electronics, rather than leaving the function in the vehicle electrical system. Under this condition, when the UNISTIK™ system is turned off, it is no longer possible to operate the flasher lights. This should be changed in future models of UNISTIK™. No correction is intended for this prototype.

4.3 FUNCTIONAL/PERFORMANCE LIMITATIONS

4.3.1 Manual Secondary Controls

Experience during Phase II testing has shown that the manually operated secondary controls, even with the use of the multi-axis joystick, are difficult for many handicapped individuals and somewhat difficult for able-bodied drivers to use while driving. Handicapped individuals with a single usable extremity could not use such manual controls in driving conditions. Their usable extremity is consumed with the primary joystick control task. The only practical secondary control method for severely handicapped users who still have voice capability would be voice actuated controls. This method would also allow for more functions than can be incorporated in multi-axis joysticks. Some preliminary work has been done to demonstrate the feasibility of secondary function voice control in the UNISTIK™ prototype but more work is needed before it could be implemented in the present or future UNISTIK™ models.

4.3.2 Alternate Drive Gear Selection

In the present UNISTIK™ design, all transmission gear selection is prevented while the vehicle is moving. While in drive, this prevents the driver from being able to accidently select reverse while the vehicle is moving. This design, however, prevents selection of one of the alternate lower drive gears, drive 1 or drive 2, to control the vehicle's speed while descending steep hills. In the future models of UNISTIK™, a feature should be included whereby these alternate drive gears can be selected while the vehicle is moving but still prevent accidental engagement of reverse or park.

4.4 SYSTEM PACKAGING LIMITATIONS

The present prototype of the UNISTIK™ system contains several packaging aspects which should be improved, wherever possible, in production models. This would reduce system cost, and reduce required installation and maintenance time for the system. It would also improve reliability of the system. Five of these aspects are briefly discussed in the following paragraphs.

4.4.1 Shock Mounting

The present shock mounts for the main electronics enclosure and mounting assembly are not as effective as they could be. Detailed analysis of their performance has not been made, but they appear to amplify some types of shock and vibration, rather than reducing it. Before other models of UNISTIK™ are developed, the design of the shock mounts should be investigated further. A digital servo system would greatly reduce the packaging problems and possibly eliminate the need for shock mounting the electronics.

4.4.2 Vehicle Wiring Harness Interface

The existing prototype secondary controls were hard-wire spliced into the vehicle harness and required extensive testing to verify which wires were to be connected in each situation. This should be improved in future models, so that the interface to the existing vehicle wiring harness can be connected with mating connectors.

4.4.3 Number of Printed Circuit Cards

The existing prototype was fabricated with 17 printed or wire-wrapped circuit cards. In future systems, this number can be substantially reduced. With careful packaging design and by reducing the number of interconnect cables between boards, the ultimate reliability will be increased. Installation and troubleshooting time will also be reduced. Digital servos would also reduce the number of required PC boards.

4.4.4 Number/Length of Interconnection Cables

The number of interconnection cables in the existing prototype is excessive and can be reduced in future models by the reduction in circuit boards. Wherever possible, the length of cables carrying heavy currents should be reduced in length. The servo power amplifiers could be installed under the dash near the servo motors rather than in the electronic enclosure behind the driver station. This may be possible only if a digital servo system is used rather than the present analog design.

4.4.5 Circuit Component Count

The analog servo electronics design inherently involves a large number of components. Because of the low volumes to be fabricated it is not easily incorporated in custom large scale integrated circuits. The only practical method to greatly reduce component counts would be to convert the analog functions to microprocessor based digital circuits. This would also further assist in reducing numbers of PC boards and interconnection cabling requirements. Overall system reliability would be increased by the component reduction.

Section 5

CONCLUSIONS

UNISTIK™ operated well under all conditions, even when faults were introduced in the worst possible situations. The reliability of the system exceeds 99-1/2 percent between yearly inspections. Drivability was shown to be good over various terrain and weather conditions.

APPENDIX A

UNISTIK™ SYSTEM

PHASE II

DRIVING TEST PLAN

TABLE OF CONTENTS

INTRODUCTION

The purpose of this Test Plan is to outline those tests which will be performed on the UNISTIK™ PREPRODUCTION UNIT (PPU) to determine that the vehicle and UNISTIK™ System function properly, or at least controllably, under both normal and abnormal circumstances.

Normal operation characteristics will first be determined. Then various types of failures will be introduced, such as failure of power control systems in the vehicle and the UNISTIK™ System electronics, and simulated as accurately as possible to determine performance of the combined system under such failure modes. Both low speed (i.e., less than 35 mph) and high speed (i.e., greater than 35 mph) tests will be performed.

Tests will be performed only if there are reasonable assurances taken, by evaluation of earlier test data or similar tests at low speed, that the test can be performed safely by the test driver and passengers (if present), and that there is a low probability that any damage might be caused to the vehicle itself. If such safety cannot be assured, then a suspect test will not be performed.

Unless otherwise specified, a video recording of the test will be taken, with the camera mounted so as to view the driver station, driver, and the view out of the windshield. Chart recordings, as appropriate for each test, will be taken during each test.

For each normal operation test, the test will be performed first with the vehicle driven manually. Then the test will be repeated, with the vehicle driven by the joystick of the UNISTIK™ System. Normally, each manual and UNISTIK™ test will be repeated three times. Wherever possible, the same driver will be used for both the manual test and the UNISTIK™ test. For ease of test scheduling and setup, a series of manual tests may be run, followed by a series of UNISTIK™ tests, so that the electronics does not have to be initiated and shut off so often.

For the Failure Mode testing only joystick controlled operation will be used.

SECTION 1
SYSTEM NORMAL FUNCTIONAL TESTS

For the System Normal Functional Tests the vehicle and UNISTIK™ systems are to be operated in a normal manner. The tests run are to test the system under expected types of driving requirements.

1.1 SYSTEM NORMAL - LOW SPEED TESTS

Tests performed under this heading are to be performed at the Vo-Tech School parking lot. They are to be performed at speeds less than 35 mph.

1.1.1 Acceleration/Deceleration

PURPOSE OF TEST

The purpose of this test is to obtain a comparison of how smoothly the vehicle can be controlled in both manual and joystick (UNISTIK™) modes in the simple acceleration and deceleration functions.

DESCRIPTION OF TEST

The vehicle is to begin in a stationary position. The vehicle is to accelerate to 25 mph within 150 ft. (first pylon), then maintain the 25 mph speed until the second pylon is reached (second pylon is 50 ft. beyond the first pylon). Upon reaching the second pylon, the brakes are to be applied in as smooth a manner as possible in order to stop the vehicle by the time a third pylon is reached which is 100 ft. beyond the second pylon.

MANUAL TEST (1.1.1)

DATA TO BE RECORDED	RECORDER CHANNEL
Fore/Aft Acceleration	1
N/C	2
Brake Feedback Potentiometer	3
Vehicle Speed	4

JOYSTICK TEST (1.1.1J)

DATA TO BE RECORDED	RECORDER CHANNEL
Fore/Aft Acceleration	1
Brake/Throttle Joystick Position	2
Brake Feedback Potentiometer	3
Vehicle Speed	4

1.1.2 Straight Line Backup

PURPOSE OF TEST

The purpose of this test is to determine how smoothly the vehicle can be controlled in the reverse mode with the joystick. The manual mode test will provide the data to compare with the joystick control.

DESCRIPTION OF TEST

The vehicle is to be stationary at the beginning of the test. Then the vehicle is to be accelerated in the reverse direction, in a smooth manner, to the speed of approximately 10 mph within a distance of 100 ft. (until first pylon is reached). Then the speed is to be maintained for an additional 50 ft. (until second pylon is reached). Upon reaching the second pylon, a smooth deceleration is to be made to stop the vehicle at a third pylon, which is 50 ft. beyond the second pylon.

MANUAL TEST (1.1.2)

DATA TO BE RECORDED	RECORDER CHANNEL
Fore/Aft Acceleration	1
N/C	2
Brake Feedback Potentiometer	3
N/C	4

JOYSTICK TEST (1.1.2J)

DATA TO BE RECORDED	RECORDER CHANNEL
Fore/Aft Acceleration	1
Brake/Throttle Joystick Position	2
Brake Feedback Potentiometer	3
Throttle Feedback Potentiometer	4

1.1.3 Right Angle Parking

PURPOSE OF TEST

This test is to determine if the joystick control is as capable as the manual controls to allow maneuvering of the vehicle into a right angle parking stall. This test will also show any significant differences in the time required to do the task manually versus the joystick.

DESCRIPTION OF TEST

The vehicle is to start from a stationary position in an 18 ft. "roadway". The vehicle is to be driven forward and controlled as neccessary to turn right and park in a 12 ft. wide, 25 ft. long parking area.

MANUAL TEST (1.1.3)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
N/C	2
N/C	3
Brake Feedback Potentiometer	4

JOYSTICK TEST (1.1.3J)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Joystick Position	1
Throttle/Brake Joystick Position	2
Throttle Feedback Potentiometer	3
Brake Feedback Potentiometer	4

1.1.4 Turnabout

PURPOSE OF TEST

The purpose of this test is to determine how similarly the joystick system can be controlled to the manual control. This test is to be a series of tight steering and braking maneuvers to accomplish the turnabout.

DESCRIPTION OF TEST

The vehicle is initially to be in a stationary position at the right side of a 25 ft. wide roadway. The vehicle is to be driven forward, turning a "hard" left, stopping, backing while turning a "hard" right, stopping, turning a "hard" left again as driving forward, to end up with the vehicle traveling in the opposite direction. This maneuver must be accomplished with the vehicle remaining within the 25 ft. wide roadway.

MANUAL TEST (1.1.4)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
N/C	2
N/C	3
Brake Feedback Potentiometer	4

JOYSTICK TEST (1.1.4J)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Joystick Position	1
Throttle/Brake Joystick Position	2
Throttle Feedback Potentiometer	3
Brake Feedback Potentiometer	4

1.1.5 Parallel Parking

PURPOSE OF TEST

The purpose of this test is to further evaluate the performance of the joystick control in comparison to the manual control of the vehicle during tight maneuvering situations, such as parallel parking.

DESCRIPTION OF TEST

The vehicle is initially to be in a stationary position in front of (i.e., the parking stall behind the vehicle) a parallel parking stall of dimensions 8 ft. wide and 25 ft. long. The vehicle is to be backed up and controlled so as to put the vehicle in the parking stall in a normal parallel parking manner.

MANUAL TEST (1.1.5)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
Throttle/Brake Joystick Position	2
Throttle Feedback Potentiometer	3
Brake Feedback Potentiometer	4

JOYSTICK TEST (1.1.5J)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Joystick Position	1
Throttle/Brake Joystick Position	2
Throttle Feedback Potentiometer	3
Brake Feedback Potentiometer	4

1.1.6 Slalom Course

PURPOSE OF TEST

The purpose of this test is to determine how the vehicle performs under hard steering maneuvers while driving forward. As usual, the reference of comparison is the manual mode of driving, which is to be compared to that of the joystick control. Of special interest for this test is to compare the speed with which the vehicle can be turned from hard left to hard right turns. Also of interest is the speed at which the vehicle can negotiate the course.

DESCRIPTION OF TEST

The course consists of 5 pylons set up in a line with a spacing of 50 ft. between each pylon. The vehicle is to begin at the end of the line of pylons, with the first pylon in front of and to the left of the vehicle. The first pylon is approximately 15 ft. in front of the vehicle. The vehicle is to be accelerated as rapidly as possible, turned between the first two pylons, back through the second and third, etc. until exiting from the course at the end of the line of pylons.

MANUAL TEST (1.1.6)

<u>DATA TO BE RECORDED</u>	<u>RECORDER CHANNEL</u>
Steering Feedback Potentiometer	1
Side/Side Acceleration	2
Fore/Aft Acceleration	3
Vehicle Speed	4

JOYSTICK TEST (1.1.6J)

<u>DATA TO BE RECORDED</u>	<u>RECORDER CHANNEL</u>
Steering Feedback Potentiometer	1
Side/Side Acceleration	2
Steering Joystick Position	3
Vehicle Speed	4

1.1.7 <u>Emergency Stop</u>

PURPOSE OF TEST

The purpose of this test is to determine how the system and the vehicle behave under rapid stopping maneuvers. It is also of interest how controllable the vehicle is under such maneuvers.

DESCRIPTION OF TEST

The vehicle is initially to be stationary. The vehicle is then to be accelerated in a straight line to a speed of 30 mph. Then the brakes are applied, "hard" on, so as to stop the vehicle as fast as possible. Control of the vehicle's direction of travel is to be attempted as the vehicle is stopped.

MANUAL TEST (1.1.7)

DATA TO BE RECORDED	RECORDER CHANNEL
N/C	1
Brake Feedback Potentiometer	2
Fore/Aft Acceleration	3
Vehicle speed	4

JOYSTICK TEST (1.1.7J)

DATA TO BE RECORDED	RECORDER CHANNEL
Throttle/Brake Joystick Position	1
Brake Feedback Potentiometer	2
Fore/Aft Acceleration	3
Vehicle Speed	4

1.1.8 Obstacle Avoidance

PURPOSE OF TEST

The purpose of this test is to test the response and controllability of the vehicle when manual and joystick controls are used to perform emergency evasive maneuvers while the vehicle is moving. This particular test is to be performed at the rather low speed of 25 mph to initially get a feel for the vehicle responses.

DESCRIPTION OF TEST

For this test, two parallel, 12 ft. wide lanes are to be used. A marker pylon is to be placed between the two lanes at the entry to the maneuver area. 50 ft. beyond this pylon, a barrier of pylons is to be placed across the right lane, (i.e., the normal driving lane). 60 ft. beyond this barrier, a similar barrier is to be placed across the left lane.

During the test, the vehicle is to be accelerated in the right lane, toward the first barrier. A speed of 25 mph is to be achieved before reaching the first pylon marker. Upon reaching this pylon, the vehicle is to be maneuvered by braking and turning to the left as neccessary, to avoid the barrier in the right lane. Then the vehicle is to be rapidly turned again to the right to avoid the barrier in the left lane. The vehicle is to end up driving straight ahead in the right lane at the end of the test area.

MANUAL TEST (1.1.8)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
Side/Side Acceleration	2
Brake Feedback Potentiometer	3
Fore/Aft Acceleration	4

JOYSTICK TEST (1.1.8J)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
Side/Side Acceleration	2
Brake Feedback Potentiometer	3
Fore/Aft Acceleration	4

1.2 SYSTEM NORMAL - HIGH SPEED TESTS

These tests are to test the normal functional performance of the vehicle and UNISTIK™ system under driving conditions at speeds above 35 mph and up to 55 mph.

1.2.1 Acceleration/Deceleration

PURPOSE OF TEST

The purpose of this test is to verify the basic system performance in higher speed tests. One of the prime objectives is to see that the switching from high gain steering at low speeds to low gain steering at higher speeds occurs properly. This test is to be a preliminary test for those which follow. It also allows for the driver to become familiar with the joystick control at higher speeds.

DESCRIPTION OF TEST

A straight road with very little or no traffic is to be used for this test. The vehicle is initially to be stationary for this test. The vehicle is to be accelerated in a normal fashion, slowly, toward 55 mph. As the speed increases, the driver is to feel the controls to be sure he is in control of the vehicle. The point at which the steering gain decreases is to be observed. The amount of control necessary for the vehicle to remain in its lane is to be evaluated also. Once the vehicle has traveled some distance at 55 mph, then the vehicle should be decelerated smoothly to a stop. The manual portion of this test is only to give a comparison between how the controls are used in the two driving modes.

MANUAL TEST (1.2.1)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
Fore/Aft Acceleration	2
Side/Side Acceleration	3
Vehicle Speed	4

JOYSTICK TEST (1.2.1J)

DATA TO BE RECORDED	RECORDER CHANNEL
(Same as for Manual Test)	

1.2.2 Lane Changing

PURPOSE OF TEST

This test is to begin evaluating the response of the vehicle and UNISTIK™ System when turning at higher speeds. Again, the manual test is to acquire data to compare with the joystick test. It is also the purpose of this test to get a better feel of the differences in controllability which may or may not occur between the high gain, low speed mode and the low gain, high speed mode on the steering servo loop.

DESCRIPTION OF TEST

This test is to utilize a straight section of little-traveled roadway. The vehicle is initially to be stationary. The vehicle is to be accelerated smoothly to approximately 30 mph then the vehicle is to be steered gently to the left lane (similar to when passing another vehicle). The vehicle is to be maintained in the left lane for a few moments, until stabilized control is achieved, then the vehicle is to be steered back into the right lane again. As travel continues, the speed is then to be increased to approximately 40 mph and the lane change maneuver repeated. Finally, the speed is to be increased to 55 mph and the lane change repeated again. The vehicle is then to be smoothly stopped.

MANUAL TEST (1.2.2)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
N/C	2
Side/Side Acceleration	3
Vehicle Speed	4

JOYSTICK TEST (1.2.2J)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
Steering Joystick Position	2
Side/Side Acceleration	3
Vehicle Speed	4

1.2.3 Tire On Shoulder Of Road

PURPOSE OF TEST

This test is to begin verifying the ability of the vehicle to be controlled under abnormal driving conditions. The main purpose is to test the ability of the vehicle to be controlled by the joystick in comparison to being driven manually. A tire on the shoulder of the road is the mildest form of an abnormal condition.

DESCRIPTION OF TEST

This test is to be performed on a little-used roadway which is straight and two lanes wide. The vehicle is initially to be in the right, or normal lane, and stationary. The vehicle is to be accelerated smoothly to approximately 30 mph, then turned gently to the right so that the right side vehicle tires leave the pavement and travel on the shoulder of the road, and then the vehicle is to be gently steered back to the left in order to return the vehicle to the center of the normal, or right-hand, driving lane. The vehicle is to be accelerated to approximately 40 mph and the movement repeated. Then the vehicle is to be accelerated to approximately 55 mph and the movement repeated once again. After this last movement, the vehicle is to be brought to a gentle stop.

MANUAL TEST (1.2.3)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
N/C	2
Side/Side Acceleration	3
Vehicle Speed	4

JOYSTICK TEST (1.2.3J)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
Steering Joystick Position	2
Side/Side Acceleration	3
Vehicle Speed	4

1.2.4 Emergency Stop

PURPOSE OF TEST

This test is to verify that emergency stopping is also possible at higher speeds as it is at lower speeds. It is also to verify that vehicle control can be maintained during stopping maneuvers at high speed. The manual test is to be used in comparison to the joystick control results.

DESCRIPTION OF TEST

The test is to be performed on a little-used two lane roadway. The vehicle is initially to be stationary. The vehicle is to be accelerated to approximately 40 mph then the brake is to be applied "hard" for the fastest stop possible. Control of the vehicle is to be maintained in the initial direction of travel as far as possible. After the stop, the vehicle is to be accelerated again to approximately 55 mph and the rapid stop procedure followed once again.

MANUAL TEST (1.2.4)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
Brake Feedback Potentiometer	2
Fore/Aft Acceleration	3
Vehicle Speed	4

JOYSTICK TEST (1.2.4J)

DATA TO BE RECORDED	RECORDER CHANNEL
(Same data as for manual test)	

1.2.5 Obstacle Avoidance

PURPOSE OF TEST

The purpose of this test is to find out how controllable the vehicle is under severe maneuver conditions at higher speeds. The manual control mode will be used as a reference to determine how safely such maneuvers can be made while testing the joystick control.

DESCRIPTION OF TEST

This test is to be run with the same pylon configuration as in the low speed obstacle avoidance test, except that the pylons are both separated by 60 ft. This test must be run on a little-used roadway or other location. Various runs through the course will be made at ever increasing speed in the manual control mode to determine the maximum speed at which this test should be performed within either the manual or joystick control mode. It is hoped that the test can be performed at a minimum of 40 mph, if not higher. Three tests of this course might not be taken, depending on the safety concern.

MANUAL TEST (1.2.5)

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
Brake Feedback Potentiometer	2
Side/Side Acceleration	3
Vehicle Speed	4

JOYSTICK TEST (1.2.5J)

DATA TO BE RECORDED	RECORDER CHANNEL
(Same as for manual mode test)	

SECTION 2
VEHICLE FAILURE RESPONSE TESTS

The purpose of these tests is to simulate three major types of vehicle failure, namely loss of power steering, loss of power brakes, and a flat tire, and to test how the UNISTIK™ System functions and is able to control the vehicle under these abnormal conditions. These tests will also evaluate how the driver must react differently, if at all, to maintain control under such failure conditions.

2.1 LOW SPEED VEHICLE FAILURE TESTS

These tests are to be performed at less than 35 mph and are to be done at the Vo-Tech parking lot. The results of these low speed tests are to determine if any high speed vehicle failure tests are to be performed. If proper vehicle control cannot be maintained at the low speeds, then high speed tests will not be run. High speed tests will be run only if controllability questions cannot be answered by the low speed test results. Specific high speed tests will be selected, as required by the performance questions unanswered by the low speed tests.

Only one run of each of the vehicle failure tests is to be made because of the damage which could result to the vehicle, such as overheating of the engine due to the removal of the belt which drives the power steering pump and also the water pump.

2.1.1 Power Brake Loss

To simulate the loss of power brakes, the vacuum hose which drives the power brake diaphragm is to be removed from the power brake diaphragm and plugged. Then the following tests are to be performed.

2.1.1.1 Acceleration/Deceleration

PURPOSE OF TEST

This test is to verify whether or not the vehicle can safely be brought to a stop by the brake servo system of UNISTIK™ when the brake system of the vehicle has no power assist.

DESCRIPTION OF TEST

The test is to be performed in exactly the same manner as Test 1.1.1J, with the same test data to be recorded. Only the Joystick Mode will be tested.

2.1.1.2 Emergency Stop

PURPOSE OF TEST

The purpose of this test is to see if the stopping effectiveness of the vehicle is impaired when the UNISTIK™ System is used to perform an emergency stop via the joystick, with the power brake power assist disconnected. This test is to be performed only if the results of the previous test (i.e., 2.1.1.1) have indicated that the vehicle does stop without power assist when the UNISTIK™ System is operating.

DESCRIPTION OF TEST

This test is to be performed in an identical manner to Test 1.1.7J, with the same data collected, as is defined for Test 1.1.7J.

2.1.2 <u>Power Steering Loss Test</u>

The Power Steering Loss will be effected by removing the power steering pump and water pump drive belt from the engine of the vehicle. CAUTION - the vehicle engine can only be operated for a minute or two once this belt has been removed. The engine temperature gauge must be watched closely, and when the temperature reaches near the boiling temperature, the engine must be turned off, regardless of the status of the test.

2.1.2.1 Slalom Course

PURPOSE OF TEST

The purpose of this test is to evaluate the ability of the UNISTIK™ System to steer the vehicle if the power steering assist is lost.

DESCRIPTION OF TEST

This test is to use the same slalom course as described in Test 1.1.6. The vehicle is initially to be positioned in the starting position for the course with the engine off and the UNISTIK™ System off. The power steering belt is to be removed from the engine, as mentioned above. The UNISTIK™ System is to be activated, then the video and chart recorders are to be turned on for recording the test. Finally, the vehicle engine is to be started and the vehicle is to immediately be driven through the course, as described in Test 1.1.6J. Once the course has been completed, the vehicle engine is to be turned off immediately and the video and chart recorders are to be turned off. The power steering pump belt is then to be reinstalled.

The test data to be collected in this test are to be identical to that of Test 1.1.6J.

2.1.3 Flat Tire Tests

These tests are to be performed to evaluate the vehicle controllability via UNISTIK™, with a flat front tire. The air is to be removed from the right front tire once the vehicle is in position for the respective tests. Movement of the vehicle while the tire is flat is to be minimized, to prevent undue damage to the tire. Once the tests are complete, the spare tire is to be mounted to replace the flat one.

2.1.3.1 Acceleration/Deceleration

PURPOSE OF TEST

This test is to evaluate the controllability of the vehicle via UNISTIK™, with the flat front tire, in simple acceleration and deceleration situations, prior to more extensive maneuvers.

DESCRIPTION OF TEST

The test is to be performed exactly as Test 1.1.1J., with the same data recorded. Only one test run will be made, as is the case with the earlier described vehicle failure tests.

2.1.3.2 Slalom Course

PURPOSE OF TEST

This test is to check on the controllability of the vehicle via the joystick, when the extensive turning maneuvers of the slalom course are attempted to be negotiated.

DESCRIPTION OF TEST

The test is to be performed the same as Test 1.1.6J, with the same data recorded.

SECTION 3
UNISTIK™ FAILURE RESPONSE TESTS

This series of tests is to determine how well the UNISTIK™ System will detect various categories of failures within the steering and brake servo systems and automatically switch to the secondary or backup system after such a failure has been detected. These tests are also to determine the vehicle controllability during such failures and switchover procedures. Both low and high speed tests are to be performed in this series.

3.1 LOW SPEED TESTS

The low speed tests are to be performed first in order to evaluate the system failure effects on vehicle controllability at safe as possible speeds. These tests are to be conducted at the same location, i.e., the Vo-Tech parking lot, as all previous low speed tests. The tests are to focus on turning and stopping functions, since these are the functions involved with the redundant steering and braking systems. The low speed tests are to be performed at less than 35 mph.

3.1.1 <u>Slalom Course</u>

PURPOSE OF TEST

These tests are to verify that the vehicle will maintain proper steering control under hard steering maneuvers, during a failure and switchover of the UNISTIK™ System from the primary to the secondary steering servo system. Sixteen separate failures are to be simulated during the slalom course tests. These are to be indicated by separate sub-test numbers below. The same course is to be followed for all slalom tests.

DESCRIPTION OF TESTS

The course for the slalom course tests with UNISTIK™ System failures is to be identical to that described in Test 1.1.6J. The tests are to be run with the UNISTIK™ System operational at the beginning of each test. For each form of failure to be simulated, prior to the actual test run, a method to implement the failure by switch closure or other simple method is to be installed into the UNISTIK™ System. This failure mechanism is to be tested to ensure it performs its intended function. The vehicle is to be positioned at the start of the course, as was done in Test 1.1.6J, the system is to be initiated, chart and video recorders are to be started, and the course is to be run as described in Test 1.1.6J. During the middle (approximately) of the course run, the "fault" is to be initiated by the test control person in the vehicle. The driver is to attempt to maintain his planned course, and keep the vehicle under control during the failure sensing and switchover process.

The sixteen different test "faults" are described below. The test data to be recorded during each test will be the same and is listed following the individual test descriptions.

3.1.1.1 Steering Power Amplifier Power Loss

The loss of power to the steering power amplifier is to be simulated by removal of the fuse which provides power to the primary steering power amplifier. An alternate method which could be used and allow for remote (i.e., from the passenger seat) triggering of the fault would be to install a switch in place of the fuse. This switch would be attached to the power amplifier via a cable which would reach to the passenger seat area and allow for triggering the fault as desired.

3.1.1.2 Steering Power Amplifier Command Failure

There are several voltage levels the steering power amplifier command signal could "freeze" at if a total failure of this signal was to occur. For these tests, a switch is to be installed in the steering power amplifier command signal line where it exits the low level analog circuit card. This switch is to be wired remote, reachable from the passenger seat. The "normal" position of the switch will allow the signal to operate the power amplifier as the system was designed to do. In the "fault" position, the switch will disconnect the amplifier command signal from the low level electronics and connect the amplifier command to a fixed voltage level. Several different voltage levels are to be used during this test series: 5V, 3V, 7V, 0V, and 12V. A separate run through the course is to be made for each one of the above listed "fault" voltages replacing the proper command signal when the "fault" switch is activated during the run of the course. The test numbers are to be designated as follows: 5V = 3.1.1.2a, 3V = 3.1.1.2b, 7V = 3.1.1.2c, 0V = 3.1.1.2d, 12V = 3.1.1.2e.

3.1.1.3 Steering Power Amplifier Command Offset Voltage Failure

This test is similar to 3.1.1.2, in that an error in the power amplifier command signal is to be simulated. In this case, however, an offset voltage is to be summed into one of the operational amplifiers in the low level analog circuit of the steering servo electronics, instead of switching to a separate voltage entirely. A low level of offset voltage is to be used, such that the microprocessor is just capable of detecting it. This voltage should be approximately 100 to 200 mv in level, i.e., equivalent to approximately 5% to 10% of the full joystick signal level. This error voltage is to be summed into the circuit by activating a switch at the desired time during the course run.

3.1.1.4 Steering Joystick Signal Failure

For these tests, the signal from the primary steering joystick potentiometer is to be disrupted via a switch installed where this signal enters the low level steering circuit card. Three types of failure in this voltage signal are to be simulated. The correct signal is to be replaced by the following signals and separate test runs are to be made while activating each voltage fault. The three "fault" signals to be used are: 0V, 12V, and an open circuit. The test number designations are to be as follows: 0V = 3.1.1.4a, 12V = 3.1.1.4b, Open Circuit = 3.1.1.4c.

3.1.1.5 Steering Feedback Signal Failure

These tests are to be identical to Test 3.1.1.4 except that the "fault" is to be inserted in the steering feedback signal rather than the steering joystick signal. The same "fault" signals of 0V, 12V, and an open circuit are to be inserted for the three test runs. The test number designations are to be as follows: 0V = 3.1.1.5a, 12V = 3.1.1.5b, Open Circuit = 3.1.1.5c.

3.1.1.6 Tachometer Signal Failure

For this test, a switch is to be inserted in the signal line where the tachometer signal enters the low level steering card. When the "fault" signal is activated during the course run, the proper tachometer signal is to be replaced by an open circuit.

3.1.1.7 Microprocessor Watchdog Failure

This test will not affect a particular servo system, such as the steering servo, but will check out what happens to the system in general, when the microprocessor detects the watchdog signal failure. The system should just place a message to that effect on the message display, and not affect any of the operational system. This failure is to be implemented by inserting a switch in the signal line for the watchdog circuit, on the microprocessor card. When the "fault" is switched in, during a slalom course run, the watchdog signal will be lost, and the microprocessor should detect this and activate the proper message.

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Joystick Position	1
Steering Feedback Potentiometer	2
Steering Amp Command	3
Side/Side Acceleration	4

3.1.2 Deceleration

PURPOSE OF TEST

This series of tests is to evaluate the effects of various types of UNISTIK™ failures upon the brake servo system. Of particular importance are the changes in stopping distance required if a system failure is experienced during a normal deceleration maneuver.

DESCRIPTION OF TEST

These tests are to be performed with the same pylon layout and driving pattern as Test 1.1.1J. During the deceleration phase of the run a "fault" is to be activated, according to one of those which are described below, and the resulting effect on vehicle performance is to be recorded. Chart recorder data identical to Test 1.1.1J are to be recorded. The following paragraphs describe the "faults" or failures which are to be simulated during these Deceleration Tests.

3.1.2.1 Brake Power Amplifier Power Loss

The loss of power to the brake power amplifier is to be simulated by removal of the fuse which provides power to the primary brake power amplifier. An alternate method which could be used and allow for remote (i.e., from the passenger seat) triggering of the fault would be to install a switch in place of the fuse. This switch would be attached to the power amplifier via a cable which would reach to the passenger seat area and allow for triggering the fault as desired.

3.1.2.2 Brake Power Amplifier Command Failure

There are several voltage levels the brake power amplifier command signal could "freeze" at if a total failure of this signal was to occur. For this test, a switch is to be installed in the brake power amplifier command signal line where it exits the low level analog circuit card. This switch is to be wired remote, reachable from the passenger seat. The "normal" position of the switch will allow the signal to operate the power amplifier as the system was designed to do. In the "fault" position, the switch will disconnect the amplifier command signal from the low level electronics and connect the amplifier command to a fixed voltage level. Several different voltage levels are to be used during this test series: 5V, 3V, 7V, 0V, and 12V. A separate run through the course is to be made for each of the listed "fault" voltages replacing the proper command signal when the "fault" switch is activated during the run of the course. The test number designations are to be as follows: 5V = 3.1.2.2a, 3V = 3.1.2.2b, 7V = 3.1.2.2c, 0V = 3.1.2.2d, 12V = 3.1.2.2e.

3.1.2.3 Brake/Throttle Joystick Signal Failure

For these tests, the signal from the brake/throttle joystick potentiometer is to be disrupted via a switch installed where this signal enters the low level brake circuit card. Three types of failure in this voltage signal are to be simulated. The correct signal is to be replaced by the following signals and separate test runs made while activating each voltage fault. The three "fault" signals to be used are: 0V, 12V, and an open circuit. Test number designations are to be as follows: 0V = 3.1.2.3a, 12V = 3.1.2.3b, Open Circuit = 3.1.2.3c.

3.1.3 Emergency Stop

PURPOSE OF TEST

The purpose of these tests is to establish how the vehicle performs and how controllable it is when certain UNISTIK™ failures occur during emergency stopping maneuvers.

DESCRIPTION OF TEST

These tests are to be performed in the same manner as Test 1.1.7J. During the stopping maneuver, the "fault" is to be switched in, and the resulting effects on the vehicle performance and maneuverability are to be recorded.

The faults which will be implemented are to be identical to those in Test 3.1.2. The data to be recorded is also to be identical to that in Test 3.1.2. The test number designations are to use similar number and letter sequences as those of Test 3.1.2 except 3.1.3 is to be substituted.

3.2 HIGH SPEED TESTS

These tests will be performed if the low speed tests are successful in showing that the vehicle remains controllable during UNISTIK™ failures at low speeds. The high speed tests will give an indication of what can be expected in the way of vehicle movements and reactions during such failures, while normal driving maneuvers at higher speeds are being executed.

3.2.1 Lane Maintenance

PURPOSE OF TEST

The purpose of these tests is to verify that the vehicle is controllable under conditions of UNISTIK™ failures at higher speeds. This initial series of high speed tests are to evaluate steering system failures, with vehicle traveling along a straight road. These tests are to be a preliminary test for those which follow.

DESCRIPTION OF TEST

A straight road with no traffic or a long paved area such as an airport runway is to be used for these tests. The tests are to be repeated for each failure simulation which is described below. Also, the tests are to be performed twice, once at 40 mph and the second time at 55 mph.

The vehicle is initially to be stationary for this test. The vehicle is to be accelerated in a normal fashion toward the desired speed (i.e., 40 mph or 55 mph). As the speed reaches the desired rate, then the "fault" to be tested is to be activated. The driver is to attempt to maintain control of the vehicle and continue at the same speed and direction as prior to the "fault". The amount of control neccessary for the vehicle to remain in its lane is to be evaluated also. Once the vehicle has traveled some distance after the "fault" then the vehicle is to be decelerated smoothly to a stop.

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Joystick Position	1
Steering Feedback Potentiometer	2
Side/Side Acceleration	3
Vehicle Speed	4

3.2.1.1 Steering Power Amplifier Power Loss

The loss of power to the steering power amplifier is to be simulated by removal of the fuse which provides power to the primary steering power amplifier. The alternate method would be to install a switch in place of the fuse, as in Test 3.1.1.1. The test number for the 40 mph test is to be 3.2.1.1a and for 55 mph is to be 3.2.1.1b.

3.2.1.2 Steering Power Amplifier Command Failure

A method identical to Test 3.1.1.2 is to be used to simulate the various "fault" voltages the steering power amplifier could go to. The voltages to be used are: 5V, 3V, 7V, 0V, and 12V. A separate run through the course is to be made for each one of the above listed "fault" voltages replacing the proper command signal when the "fault" switch is activated during the run of the course. Test number designations are to be as follows: 5V = 3.2.1.2a, 3V = 3.2.1.2b, 7V = 3.2.1.2c, 0V = 3.2.1.2d, 12V = 3.2.1.2e for 40 mph; and for 55 mph the test numbers are to be 3.2.1.2f through j respectively.

3.2.1.3 Steering Power Amplifier Command Offset Voltage Failure

These tests are similar to 3.2.1.2, in that an error in the power amplifier command signal is to be simulated. In this case, however, an offset voltage is to be summed into one of the operational amplifiers as is to be done in Test 3.1.1.3. This voltage should be approximately 100 to 200 mv in level, i.e., equivalent to approximately 5% to 10% of the full joystick signal level.

This error voltage is to be summed into the circuit by activating a switch at the desired time during the course run. Test number designations are to be 3.2.1.3a for 40 mph and 3.2.1.3b for 55 mph tests.

3.2.1.4 Steering Joystick Signal Failure

For these tests, the signal from the primary steering joystick potentiometer is to be disrupted via a switch installed where this signal enters the low level steering circuit card. Three types of failure in this voltage signal are to be simulated. The correct signal is to be replaced by the following signals and separate test runs made while activating each voltage fault. The three "fault" signals to be used are: 0V, 12V, and an open circuit. The failures are to be simulated in an identical manner as in Test 3.1.1.4. Test number designations are to be as follows: for 40 mph, 0V = 3.2.1.4a, 12V = 3.2.1.4b, and Open Circuit = 3.2.1.4c; for 55 mph, 0V = 3.2.1.4d, 12V = 3.2.1.4e, and Open Circuit = 3.2.1.4f.

3.2.1.5 Steering Feedback Signal Failure

These tests are to be identical to Test 3.2.1.4 above except that the "fault" is to be inserted in the steering feedback signal rather than the steering joystick signal. The same "fault" signals of 0V, 12V, and an open circuit are to be inserted for the three test runs at each speed. Test number designations are to be as follows: at 40 mph, 0V = 3.2.1.5a, 12V = 3.2.1.5b, and Open Circuit = 3.2.1.5c; at 55 mph, 0V = 3.2.1.5d, 12V = 3.2.1.5e, and Open Circuit = 3.2.1.5f.

3.2.1.6 Tachometer Signal Failure

For these tests, a switch is to be inserted in the signal line where the tachometer signal enters the low level steering card. When the "fault" signal is activated during the course run, the proper tachometer signal is to be replaced by an open circuit. Test number designations are to be as follows: at 40 mph = 3.2.1.6a, at 55 mph = 3.2.1.6b.

3.2.2 Lane Changing

PURPOSE OF TEST

These tests are to evaluate the response of the vehicle and UNISTIK™ System when turning at higher speeds, during which the UNISTIK™ System fails.

DESCRIPTION OF TEST

These tests are to use a location similar to that of Test 3.2.1. The tests are to be performed at both 40 mph and 55 mph. At each speed, each "fault" is to be tested in a separate run at that speed. The vehicle is initially to be stationary. The vehicle is to be accelerated smoothly to the test speed, then the vehicle is to be steered gently to the left lane (similar to when passing another vehicle). The vehicle is to be maintained in the left lane for a few moments, until stabilized control is achieved, then the vehicle is to be steered back into the right lane. Then the vehicle is to be smoothly stopped. During the turning or lane change maneuver, the "fault" is to be activated. The faults to be tested will be identical to those of Test 3.2.1. Similar test number letters apply to these tests as to the tests described in Test 3.2.1.

DATA TO BE RECORDED	RECORDER CHANNEL
Steering Feedback Potentiometer	1
Steering Joystick Position	2
Side/Side Acceleration	3
Vehicle Speed	4

3.2.3 Deceleration

PURPOSE OF TEST

This series of tests is to evaluate the effects of various types of UNISTIK™ failures upon the brake servo system at the higher speeds. Of particular importance will be the changes in stopping distance required if a system failure is experienced during a normal deceleration maneuver.

DESCRIPTION OF TEST

This test is to be performed at the same location as that of Tests 3.2.1 and 3.2.2. Two speeds (40 mph and 55 mph) are to be used for the tests. The vehicle is to be smoothly accelerated from a stationary position to the desired speed for the particular test, then the vehicle is to be smoothly decelerated back to a stopped position. During the deceleration phase of the run, a "fault" is to be activated, according to one of those which are described in Tests 3.1.2, and the resulting effect on vehicle performance is to be recorded. The "faults" or failures which are to be simulated during these deceleration tests will be identical to those for Test 3.1.2. Test number designations are to be similar to those of 3.1.2 for the 40 mph tests, and the 55 mph test designations being a continuation of the letter designations in each case.

DATA TO BE RECORDED	RECORDER CHANNEL
Brake/Throttle Joystick Position	1
Brake Feedback Potentiometer	2
Brake Amplifier Input	3
Fore/Aft Acceleration	4

APPENDIX B

UNISTIK^{TM} SYSTEM

PHASE II

BENCH TEST PLAN

TABLE OF CONTENTS

Section 1

INTRODUCTION

The purpose of this test plan is to outline those tests which will be performed on the UNISTIK™ Preproduction Unit (PPU) itself in the laboratory or UNISTIK™ subsystems thereof on the bench to accomplish accelerated life testing on the major primary system components of the UNISTIK™ system.

The major primary system components of the UNISTIK™ system are the steering, brake, throttle, and transmission servo loops. These are the basic elements controlling the vehicle. These servo loops are very similar to one another. It has been decided that the steering servo system will be the main system tested, as being representative of the other servo loops. It is also one of the most complicated servo loops, and has the highest component count.

The low level servo electronics board and high power steering amplifier will be bench tested for extended periods at high temperature, using generated signal inputs and a passive load on the power amplifier.

The servo mechanical mechanisms, including motor, gearing, feedback potentiometers, etc, will be tested by extensive cycling within the vehicle itself, while set up in the laboratory. The brake servo will be cycled in the same fashion, to accelerate any possible wear on this system. These mechanical tests will be at room temperature.

Test data will be recorded during all tests at intervals so any changes with time will be detected. A chart recorder or computer memory will be used to record the test data.

The following sections describe the tests in more detail.

Section 2

STEERING/BRAKE MECHANICAL LIFE TEST

2.1 PURPOSE OF TEST

The purpose of this test is to exercise the steering and brake servo mechanical systems while in the vehicle so the mechanical loading is as close to the actual operating loads seen by the system as is practical to achieve. There will be some differences, however, as the power steering and power brake boost systems of the vehicle will not be activated. The microprocessor unit (MPU) in the UNISTIK™ will be programmed to exercise the systems continuously for an extended period to put as much usage on the mechanical components as would normally occur in 10 years of actual use. This extensive use will allow determination of what components may be prone to failure or wear during such a usage period, and when preventive maintenance and inspections should be performed on these mechanical systems.

2.2 DESCRIPTION OF TEST

The van with the UNISTIK™ system installed will be set up in the laboratory. The front end will be jacked up so that most vehicle load (not all) is off the front tires. The front tire loading will be adjusted until the steering force required is similar to when the vehicle is normally operated with power steering activated.

The brake servo system will not be adjusted in any way to correct for the lack of power brake assistance normally available from the engine vacuum. This will place a possibly higher load on the brake servo system, but since the brake servo is a force servo anyway, this should not significantly effect the forces involved on the brake servo during the test.

The MPU in UNISTIK™ will be programmed to function continuously in a mode, similar to testing the UNISTIK™ during start up procedures. The computer will be programmed to provide the following functions, in the order shown and for the time periods indicated below:

No.	Function	Magnitude	Time held
1	Steering	7 Volts	5 Seconds
2	Brake	7 Volts	5 Seconds
3	Brake	5 Volts	15 Seconds (During functions 1,4&5)
4	Steering	3 Volts	5 Seconds
5	Steering	5 Volts	5 Seconds

This sequence will be repeated continuously while the test is in process. The test will be run from 8 a.m. Monday morning until 5 p.m. Friday afternoon for two consecutive weeks, if a malfunction does not cause premature test termination.

The above described test sequence will drive the steering wheel from center to extreme right, then back to center, brake to full brake force then back to neutral position, steering to full left position, then back through center to extreme right position again as the cycle repeats.

During the test operation, the MPU will monitor system steering and brake reaction to the test signals in a manner similar to the start up procedure. If an out-of-tolerance response is measured, the test will be automatically terminated and an error message stored in battery backed RAM memory as to the cause of the test termination. The MPU should also monitor heat sink temperatures for both steering and brake power amp and terminate the test if excessive temperature is sensed.

2.3 DATA TO BE RECORDED

Once each hour, the following data is to be recorded by the MPU and stored in the battery backed RAM memory for later retrieval, analysis, and archiving.

Test Cycle	Data Point	Number Points/Cycle
Steering 7 Volts	Position Feedback	10
Steering 7 Volts	Tach Feedback	10
Steering 7 Volts	Amp Command	10
Steering 7 Volts	Amp Current	10
Steering 7 Volts	Steering Heat Sink Temp	1
Brake 7 Volts	Amp Command	10
Brake 7 Volts	Amp Current	10
Brake 7 Volts	Brake Heat Sink Temp	1
Brake 5 Volts	Amp Current	10
Steering 3 Volts	Position Feedback	10
Steering 3 Volts	Tach Feedback	10
Steering 3 Volts	Amp Command	10
Steering 3 Volts	Amp Current	10
Steering 5 Volts	Position Feedback	10
Steering 5 Volts	Tach Feedback	10
Steering 5 Volts	Amp Command	10
Steering 5 Volts	Amp Current	10

The 10 samples of each data point will be equally spaced over the 5 second interval at each position test cycle, i.e., data should be taken at 0.5 second intervals, with the exception of the Brake 5 volt position. This data may be taken at 1.5 second intervals. If practical, the data stored for voltage signals will be converted to volts, currents to current, and temperature to degrees Fahrenheit before storage in the memory.

At the conclusion of the test period (10 days), the mechanical servo components for steering and brake servo should be dissassembled, checked, and inspected for wear and other damage. All inspection and check results will be documented in engineering notebooks.

Section 3

STEERING SERVO ELECTRONICS TESTS

3.1 PURPOSE OF TESTS

The purpose of these tests is to evaluate the performance of typical servo electronics for the UNISTIK™ system under extended testing at elevated temperature. The extended testing at elevated temperature will give indications of the expected life cycle of these electronics prior to failures requiring repair.

The temperature cycling test will provide information on the performance of the UNISTIK™ servos under ambient temperature extremes to be seen by actual vehicle use in various seasons and locations.

During the temperature cycling test, the power supply voltage will be varied over the range of 10.6 volts DC to 13.4 volts DC to evaluate electronics performance under combined temperature and voltage extremes. These voltage levels are representative of those observed in the vehicle environment.

3.2 DESCRIPTION OF TESTS

A low level steering servo wire wrap card will be fabricated. A steering power amplifier module complete with heat sink, low level amplifier PC board, and full temperature range ICs will also be fabricated for this test.

If possible, the fan which is normally used in conjunction with the power amplifiers will not be used during the test. This will evaluate how reliable the units will be if the fans are not functioning or are not included in future models of the UNISTIK™.

A temperature sensor will be installed on the power amplifier heat sink (as usual). An additional temperature sensor will be installed on the low level servo board. This latter sensor will be used to verify the "ambient" temperature of the electronics modules during the test when the units are in the test chamber.

The low level and power amplifier modules are to be placed in a temperature oven for the tests. DC power is to be supplied by a high current HP supply. A resistive load will be provided for the power amplifier output which can handle at least 200 watts continuous power dissipation.

Simulated input signals will be provided to the low level servo electronics for the following inputs: joystick signal, position and tach feedback signals, and vehicle speed input.

The input signals will be as illustrated in Figure 1.

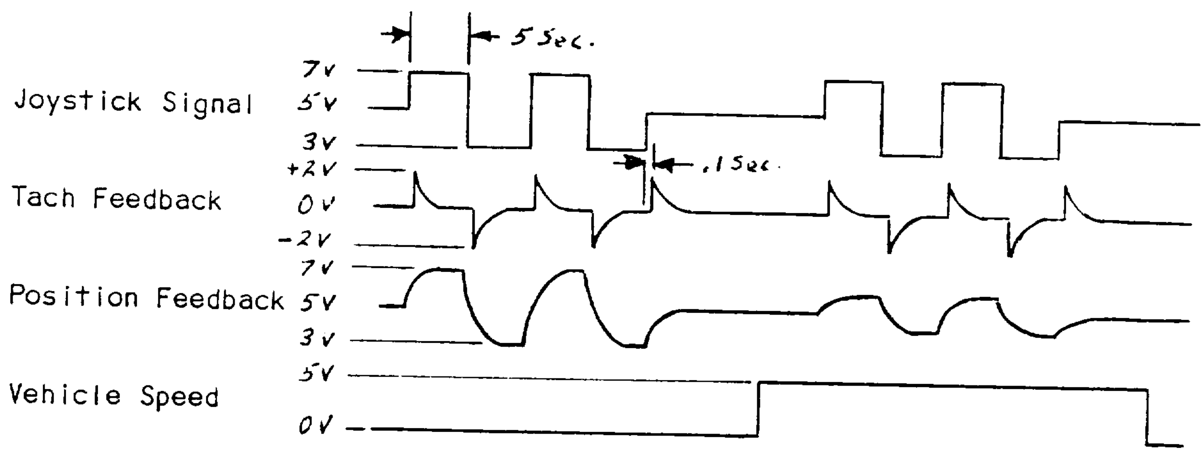


FIGURE 1. ANALOG VOLTAGE WAVEFORMS INPUT TO LOW LEVEL SERVO CARD.

The amplitude and filtering of the waveforms for tach and position feedback will be adjusted to allow the low level card output (amp command) to reach zero before the end of each voltage level applied via the joystick signal.

The waveforms shown in Figure 1 are to be generated via computer or dedicated electronic hardware. The waveforms are to repeat over and over again throughout the duration of each test.

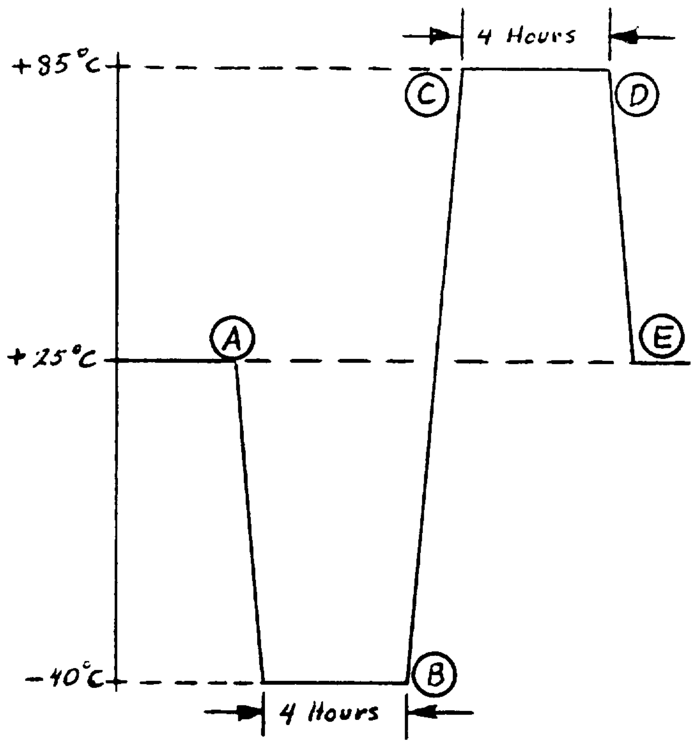
The test will be performed in accordance with the temperature patterns to be used for each test (see Sections 3.2.1 and 3.2.2) with the input signals and power applied when indicated in Sections 3.2.1 and 3.2.2. The electronics will be powered by the DC supply. Test data will be taken as described in Sections 3.2.3 and 3.2.4. Power supply voltage operations will be set to the levels specified in Sections 3.2.3 and 3.2.4.

3.2.1 <u>Description of Test for Temperature Cycling</u>

The servo electronics will be installed in the temperature chamber and connected with input signals, power, and resistive load as described in Section 3.2.

The temperature chamber will be operated according to the temperature profile of Figure 2.

At the start of the test at room temperature, the data (as defined in Section 3.2.3) will be taken. The chamber will be changed to the first temperature of Figure 2, the temperature stabilized, and the test data recorded again. This is repeated at each temperature plateau on the temperature profile. The unit will then be returned to room temperature and input signals and power removed.



Power and Signals to be applied and data taken at points A,B,C,D and E.

Power and Signals are removed after each data gathering is completed.

FIGURE 2. TEMPERATURE/TIME PROFILE FOR TEMPERATURE CYCLE TEST

The temperature profile as indicated in Figure 2 will be repeated at least twice to compare test date achieved. If large discrepancies exist then a third run will be performed.

3.2.2 Description of Test for Extended High Temperature Test

For this test the electronics will be placed in the temperature chamber, at room temperature under power and input signals for checkout.

The test data listed in Section 3.2.4 will be recorded. Then the temperature in the chamber will be raised to 140° F and maintained there (+3° F) for 168 hours. The electronics will remain under power and input signals during regular working hours when someone is attendant.

Test data will be recorded every hour during working hours (while the system is under power) according to the description in Section 3.2.4.

Once the test is complete, the unit will have power and signals removed and then be returned to room temperature, where a final power-up data taking task will be performed.

A power supply voltage of 13.4 VDC is to be used at all times the electronics are powered for this test.

3.2.3 Test Data for Temperature Cycle Test

The following data will be recorded via chart recorder at each of the three power supply voltages of 10.6VCD, 12.0 VDC and 13.4VDC at each of the designated points on the temperature profiles of Figure 2, i.e., points A through E. The time of the data recording and test number should be noted on the chart recording.

1. Joystick Input Signal
2. Amp Command Signal
3. Power Amp Current
4. Heat Sink Temperature/Low Level Card Temperature (Alternate Recordings)

3.2.4 Test Data for Extended High Temperature Test

The data to be recorded via chart recorder are as follows:

1. Joystick Input Signal
2. Amp Command Signal
3. Power Amp Current
4. Heat Sink Temperature/Low Level Temperature (alternate recordings)

The data will be gathered at the start of each test day and every hour during the day and again at the end of each test day (working hours). The data will also be taken at room temperature before the test starts and again at room temperature after the test ends.

The data will be gathered with the power supply voltage set at 13.4 volts. This will also provide additional stress to aid in the accelerated life testing process.

The time of each data recording and the test number will be noted on the chart recording.

If a problem occurs during either test described above or the recorded signals look incorrect, a separate recording of these input signals will be made to verify inputs are correct.

1. Joystick Input Signal
2. Tach Feedback Signal
3. Position Feedback Signal
4. Vehicle Speed Input

APPENDIX C

UNISTIK^{TM} SYSTEM

PHASE II

TEST RESULTS

TABLE OF CONTENTS FOR APPENDIX C

Section 1

SYSTEM NORMAL - FUNCTION TESTS

1.1 SYSTEM NORMAL - LOW SPEED TESTS

1.1.1 Acceleration/Deceleration

The accelerations and decelerations for both the manual mode and the UNISTIK™ system were very comparable. In both cases, smooth accelerations and decelerations can be accomplished with relative ease. A typical response for manual driving is shown in Figure C-1. A similar response for the UNISTIK™ mode is shown in Figure C-2. It can be seen from the two figures that the acceleration (fore-aft) is very similar for the two driving methods.

The braking function with the UNISTIK™ system was quite sensitive and had to be practiced a few times to get smooth braking. Once experience was gained, then smooth braking was possible by the UNISTIK™ system as shown in Figure C-2.

Since full throttle and brake travel are possible with UNISTIK™, the same performance range is possible with UNISTIK™ as with manual control.

1.1.2 Straight Line Backup

Backing up was similar to the forward acceleration/deceleration test results, except that braking was even more "touchy" in reverse and required extra care to provide smooth stopping from reverse travel. Figure C-3 shows a chart recording for manual driving for straight line backup. Figure C-4 shows the same information for using the UNISTIK™ system. Note in this case, the peak acceleration reached while stopping, using the UNISTIK™ system, was over 50% higher, indicating more rapid deceleration. Typical results with UNISTIK™ were 50% to 100% greater reverse travel decelerations than when driven manually. A strong tendency existed to over-control the braking, let up, then re-brake again. This can be seen in Figure C-4.

Reverse accelerations were essentially the same for both manual driving and driving with the UNISTIK™ system.

1.1.3 Right Angle Parking

The vehicle was fully maneuverable in either the manual driving mode, or using the UNISTIK™ system. Therefore, in both cases, the right angle parking maneuver could be performed. Parking performance with the UNISTIK™ system was more tentative, due to the lack of familiarity with it. During the maneuver the vehicle was driven more slowly with UNISTIK™, with very little throttle given during the maneuver. After three attempts, the time for the manual maneuver was 20 seconds. The time for the UNISTIK™ maneuver after three attempts was 31 seconds.

1.1.4 Turn-About

Characteristics of the turn-about were similar to the right angle parking maneuver. Maneuvers were slower with the UNISTIK™ system. The manual maneuver required 39 seconds and 65 seconds were required with UNISTIK™. The brakes were typically applied harder during maneuvering with the UNISTIK™. Both driving methods took the same number of maneuvers to complete the turn-about, namely, a hard left turn, hard right turn, then another hard left.

1.1.5 Parallel Parking

The manual parking maneuver took 31.5 seconds on the third attempt, and the UNISTIK™ maneuver took 45.5 seconds on the third attempt. The difference in familiarity between the two driving modes contributed to the differences measured. Some "tentativeness" was observed during the UNISTIK™ maneuvers, as with earlier described tests. Another reason for slower responses when using the UNISTIK™ is that during gear changes, the hand is removed from the joystick. The steering then returns to the center position, requiring a re-turning maneuver, if a continuation of the turn is required after shifting.

1.1.6 Slalom Course

Figure C-5 shows chart recordings of manual driving of the slalom course. Figure C-6 shows recordings of the course being driven with the UNISTIK™. Note that the chart speeds are different for the two figures in this case. These figures are for the third run through the course in each case.

During the three manual runs through the slalom course, the peak accelerations improved 16% (on average) from the first to the third run. During the UNISTIK™ runs, the improvement averaged 40% from the first to third runs.

Comparing the results for the third run in each driving mode, the following is apparent: The maximum speed obtained during the third run was 15% to 20% higher for UNISTIK™ driving than for manual driving. Likewise, the UNISTIK™ run achieved a 19% higher peak lateral acceleration. The time between acceleration peaks (direction reversals) was 2.0 seconds for the manual driving mode but only 1.75 seconds for the UNISTIK™ driving mode (a 13% faster response for UNISTIK™ control).

The steering response appeared to be nearly as smooth with the UNISTIK™ as with manual driving.

1.1.7 Emergency Stop

In this test, the results are nearly identical for the manual and UNISTIK™ modes (see Figures C-7 and C-8). In each case, the wheels "locked" when the brakes were applied. The deceleration curves were nearly identical, with the peak decelerations being the same and the time required to stop being approximately the same, at 2.5 seconds in each case. Top speed reached before brakes were applied was about 30 miles per hour in both cases. The only noticeable difference between the two test modes was that in the manual mode, the brakes were released sooner as the vehicle stopped, and therefore the deceleration curve was slightly more sloped at the end of the stop for the manual mode than for the UNISTIK™ mode.

1.1.8 Obstacle Avoidance

In the first of a series of three runs through the obstacle course, the UNISTIK™ mode of driving showed higher peak lateral accelerations and faster steering movements than the manual mode. Peak accelerations were about 25% higher in the UNISTIK™ mode. In the last of the three runs, the peak accelerations were about 15% less than the first run, for manual mode, but were approximately 40% less than the first run for the UNISTIK™ mode. Figure C-9 shows the chart of the third run for manual mode. Figure C-10 shows the third run for the UNISTIK™ mode.

The steering movements were faster (peak to peak) for the UNISTIK™ mode. In the third run, the time between peak to peak wheel movement was 1.25 seconds for the UNISTIK™ mode, compared to 1.75 seconds for the manual mode. The main reason for this difference is in the last 0.75 seconds. The manual mode showed a very slight extra wheel movement after the initial rapid movement. In all cases, the wheel was held to the right longer for manual mode than for UNISTIK™ mode.

As the three runs progressed, and in both driving modes, less peak to peak wheel movement was made. As experience was gained, tighter turning closer to the pylons was indicated

1.2 SYSTEM NORMAL - HIGH SPEED TESTS

1.2.1 Acceleration/Deceleration

Although there was caution exercised by the driver for these first highway speed tests with the UNISTIK™ system, the driver was sufficiently confident to drive up to 60 miles per hour during the runs.

No chart recordings were made of the manual driving mode for this test. A portion of the chart for the UNISTIK™ mode driving is shown in Figure C-11.

As shown in Figure C-11, the steering wheel motions (as indicated by the steering feedback chart) normally did not exceed +/- 5 to 10 degrees of rotation. This was also verified by the video recordings.

Figure C-12 shows another UNISTIK™ run of acceleration/deceleration. In this case, once the speed approached 40 miles per hour the vehicle was slowed down to about 30 miles per hour and then accelerated to 50 miles per hour. During these speed changes, there were considerably more steering movements, indicating some difficulty in maintaining a straight course without "over-controlling". This was experienced during the fore-aft joystick motions necessary to slow the vehicle and speed up. These over-control motions are shown clearly in Figure C-12. They reached +/- 20 to 30 degrees in wheel rotation as shown by the charts and verified by the video tapes. These motions generated lateral, or side-to-side accelerations in the vehicle. Even during these "overcontrol" times, the vehicle was kept within its proper lane on the road, and no "undue" weaving of the vehicle was observed.

Although joystick motion was not charted during this test, it was considerable, as evidenced by the video tapes. The non-linear steering response required considerable joystick motions to make small corrections in the wheel position.

1.2.2 Lane Changing

Figure C-13 shows a representative chart recording of lane changing while driving in the manual mode. Lane changes at speeds of approximately 35, 45, and 55 miles per hour are shown. The side-to-side, or lateral acceleration curves indicate the occurrences of the lane change maneuver. Note that each maneuver took approximately the same time, even though three different speeds were used for the three maneuvers. Note also that more steering movement (as evidenced by the steering feedback signal) was used at the lower speeds.

Figures C-14 and C-15 show equivalent charts for runs of lane changing using the UNISTIK™ driving mode. A 30 mile per hour maneuver is shown in Figure C-14. Maneuvers for 45 and 55 miles per hour are shown in Figure C-15.

The acceleration curve (side-to-side) illustrates the maneuvers. It can be noted that the maneuvers took longer during the UNISTIK™ mode than during the manual driving mode. There was a longer period of time between each change of lane and the return to the original lane. Also, the acceleration curves indicate that at the higher speeds, the lane transitions were made more gradually when the driver was using the UNISTIK™ mode. A significant factor in this result was driver caution exercised when making these maneuvers.

During normal straight driving, between maneuvers, typical joystick excursions to maintain vehicle direction appear to be on the order of +/- 10% of total possible joystick travel. This magnitude of correction was made with a frequency range on the order of about one cycle per 2.5 to 3.5 seconds. Smaller corrections of about +/- 3% to 5% occurred very rapidly with a frequency of motion of about 0.75 seconds per cycle. These corrections were a function of road conditions, speed, and driver experience level. For the high frequency joystick motions, the wheel motion, as shown by the steering feedback curves, was minimal. Worst case wheel motions appeared to be between 25 and 30 degrees peak to peak. This was confirmed by the video tape recordings.

During lane change maneuvers, the joystick position peaked at about +/- 35% to 45% of total possible travel, and wheel position moved about +/- 35 degrees to accomplish the maneuver. Little over-correction was observed when the lane was regained after each maneuver. The acceleration curves for the manual mode and UNISTIK™ mode are very similar in this respect.

The vehicle movements felt quite similar to vehicle passengers for the manual and UNISTIK™ modes. The accelerometer signals and steering feedback signals indicated that the manual maneuvers were somewhat smoother most of the time.

1.2.3 Tire On Shoulder

Figure C-16 shows a typical chart recording of a manual mode run where the vehicle was driven so that the right tires left the road surface momentarily and then returned to normal lane travel again. Figures C-17 and C-18 show similar recordings for the UNISTIK™ driving mode.

There is little difference between the manual and UNISTIK™ test results for this test. The peak steering excursions were similar, as were the peak accelerations measured. There were variations between runs but this was due primarily to how far off the road the vehicle was driven, how long the vehicle stayed off the road before returning to its lane, and how rough the road shoulder interface was. The magnitudes of correction, once the vehicle returned to its lane, appeared to be slightly higher for the UNISTIK™ mode, but this depended on each run condition.

1.2.4 Emergency Stop

Figures C-19 through C-22 show two typical emergency stop maneuvers with manual mode and UNISTIK™ mode respectively.

Emergency stopping was very similar for both manual and UNISTIK™ modes. The vehicle reaction was mainly determined by vehicle position on road, road condition, and "set" of the steering wheel at the time of brake application. In both modes, there was at least one occasion when the driver let up on the brakes momentarily to regain control of the vehicle's direction before completing the stop. Vehicle dynamics played a dominant role in the stopping responses. In both modes, during one maneuver, the vehicle's front tire ended up off the roadway after the vehicle came to a stop.

In all cases tested, at every speed, complete stops could be implemented, with "locked" tires. Stops from 50 miles per hour required approximately 5.0 seconds.

1.2.5 Obstacle Avoidance

Figures C-23 and C-24 show typical chart recordings of obstacle avoidance maneuvers for manual and UNISTIK™ driving modes respectively. During these tests, successful negotiation of the "obstacle" was accomplished by both driving modes. In both cases, the maximum speed at entry to the test was limited for safety reasons to 40 miles per hour, because of the sharp maneuvers involved. In all cases, vehicle control was maintained through the test. The charts of lateral (side-to-side) acceleration and steering feedback indicate slightly "sharper", or not as smooth, steering movements in the UNISTIK™ mode, compared to the manual mode. It was observed, however, that the braking was not as hard or applied as long during UNISTIK™ runs through the test as with manual runs. Peak braking (for the last trial in each case) for the UNISTIK™ mode was only 57% of that applied in the manual mode. Braking was also only applied for half as long for the UNISTIK™ mode test. The speed reduction seen during a run of the course was quite similar between the two cases.

Peak accelerations were similar for both manual and UNISTIK™ modes, except for slightly higher peaks on the recovery end of the maneuvers for UNISTIK™. This indicated that there was more "overshoot" or steering corrections after the maneuvers for UNISTIK™ than for manual mode.

Section 2

VEHICLE FAILURE RESPONSE TESTS

2.1 LOW SPEED - VEHICLE FAILURE TESTS

2.1.1 Power Brake Loss

2.1.1.1 Acceleration/Deceleration

Figure C-25 shows the chart recording made during the acceleration/deceleration test with loss of vehicle power brakes. During this test, the residual vacuum was bled down in the power boost diaphragm unit. It was quickly determined that with loss of the power brake vacuum assist, the UNISTIK™ brake servo system lacked sufficient force to push the brake pedal far enough to stop the vehicle effectively. It can be seen from Figure C-25 even though the brake joystick was fully applied, the maximum brake pedal motion (as indicated by the brake feedback signal) was only 65% of maximum.

It was felt, during the test, that only 5% to 10% braking force was applied, which brought the vehicle slowly to a stop from about 8 miles per hour in about 10 seconds.

2.1.1.2 Emergency Stop

Due to the results of the power brake loss test (2.1.1.1), the emergency stop test was not performed.

2.1.2 Power Steering Loss

2.1.2.1 Slalom Course

A chart recording of the results of driving the slalom course with the UNISTIK™ system with loss of power steering is shown in Figure C-26. This test was performed at low speed to provide adequate safety margins.

The method used to disable the power steering was to shut off the vehicle engine, while leaving the UNISTIK™ system activated. This was accomplished by unplugging the secondary control electronics output cable, which removed power from the ignition circuit as well as other secondary controls. This was determined to be easier to implement than removing the power steering pump drive belt, and provided a method of initiating the fault during vehicle movement.

Once the fault was engaged, the maximum peak excursion of the steering wheel, from the position it was in when the fault was initiated, was approximately 80 degrees of steering wheel rotation. This amounted to about 12% of peak possible wheel rotation (one direction, not peak to peak). The chart recordings and video recordings verify this result. The UNISTIK™ system failed to provide sufficient force to control the vehicle steering when the power steering assist was lost.

2.1.3 Flat Tire (Front)

2.1.3.1 Acceleration/Deceleration

Figure C-27 shows the results of initial driving with the UNISTIK™ system with a flat front tire. No problems were experienced during low speed driving. The speed for this test was kept very low (i.e., too low to register on the speed sensing circuit). Steering was felt to be adequate during straight driving and during some turns made at that time.

2.1.3.2 Slalom Course

The slalom course was also driven with the flat tire. It was driven slowly so as to not damage the tire which had been deflated. Figure C-28 shows the chart recordings made during this test. No problems were encountered and the vehicle direction control was not affected in any manner by the flat tire.

Section 3

UNISTIK™ FAILURE RESPONSE TESTS

3.1 LOW SPEED TESTS

3.1.1 Slalom Course

3.1.1.1 Steering Power Amplifier Power Loss

Figure C-29 indicates the results of this test. It can be seen from this recording, and from the corresponding video recordings, that when the fuse was pulled from the steering servo power amplifier, it took approximately 0.5 seconds for the UNISTIK™ system to sense the fault and switch in the secondary steering servo system. This 0.5 second delay prevented the steering wheel from being maintained during a turn maneuver and the next pylon in the slalom course was missed. When the secondary servo switched in, however, there was no problem maintaining control of the vehicle.

3.1.1.2 Steering Power Amplifier Command Failure

Figures C-30 to C-34 show the chart recordings of the test results of this series of steering power amplifier command failures.

During this series of tests, various DC voltages were switched into the amplifier command signal line. The results correlated with the difference between the amplifier command signal before fault introduction, and the value of the signal with fault introduced. For instance, during test (b) (see Figure C-31) the fault voltage was switched to 3 volts DC shortly after the amplifier command itself had passed the 3 volt level. In this case, there was essentially no discernible variation in the steering feedback signal nor the lateral acceleration pattern at the time of the fault introduction.

When the fault error of 5 volts DC during test (a) (see Figure C-30) was switched in, the amplifier signal reversed itself from where it had been, by 1.4 volts. In this case, a hesitation, or pause, can be seen in the slope of both the steering feedback position and in the acceleration curves. This pause lasted approximately 0.1 seconds, the time required for the relay to switch in the secondary system.

In tests (a) through (d), the slight pauses in steering movement had no appreciable effect on maneuvering the vehicle through the remaining portion of the slalom course. The maximum voltage difference between the normal amplifier command signal and the error during tests (a) through (d) were found in test (c) (see Figure C-32), when the difference was 3.2 volts.

During test (e) (see Figure C-34), where 12 volts were switched into the amplifier command, the difference in voltage which occurred from the normal signal was 13.4 volts. This was nearly the maximum type of error fault possible. This error caused a slight reversal of the steering wheel by approximately 10 degrees of rotation, before the secondary steering servo took over. In this case, the steering position could not be returned to its former position and rate of change until approximately 0.2 seconds had elapsed after the fault was initiated. This delay caused the next pylon in the course to be missed, but caused no vehicle control problems or instability when the secondary system took over.

3.1.1.3 Steering Power Amplifier Command Offset Voltage Failure

During this test, a small offset voltage was inserted into one of the operational amplifier inputs to create a small error signal. This error was just large enough to be sensed, causing a switchover to the secondary steering servo electronics. The first run of this test did not cause the error to be detected. Therefore, the offset voltage was adjusted slightly higher and the test repeated. Figure C-35 shows the results of this second test. This time the error was sensed and the secondary system switched in. No indication was seen on acceleration or steering feedback signal recordings, or by the steering wheel (as seen in the video recordings) to indicate any perturbations due to this small error voltage. The amplifier command voltage was saturated on the chart recording at the time the fault was switched in, so a measure of its magnitude could not be recorded. It would have been equivalent to approximately 2.0 volts, at the amplifier command signal point.

3.1.1.4 Steering Joystick Signal Failure

Figures C-36 through C-38 show the results of this series of tests. The results of these tests, simulating joystick signal failures of shorts to ground, to power supply voltage and open circuits, respectively, did not show appreciable effects on steering position (feedback) or vehicle acceleration. A slight hesitation was shown in the open circuit test (c) (see Figure C-38). In this latter case, there was a slight steering wheel position reversal of approximately 5 degrees. This did not affect the ability of the driver to complete the slalom course in a normal fashion.

3.1.1.5 Steering Feedback Signal Failure

Figures C-39 through C-41 show the results of this test series. The faults switched into the steering feedback signal line created different direction fault voltages at the steering amplifier command signal, but the overall results were nearly identical to the previous test series (3.1.1.4).

The first two cases resulted in only slight perturbations in the steering and acceleration curves. The open circuit case, test (c) (see Figure C-41), resulted in a noticeable hesitation in the steering wheel as the fault was switched in. It did not, in this case, result in a reversal of the steering wheel rotation. The steering feedback chart also indicated a distinct plateau for about 0.12 seconds, before resumption of movement.

No control problems were noticed by the driver, and the course was successfully completed in all three cases. There is evidence, from this series of chart recordings, that the course running is becoming easier for the test driver as he gains experience. In general, the steering and joystick position curves on the charts are smoother.

3.1.1.6 Tachometer Signal Failure

Figure C-42 shows that during this test, no discernible control problems were experienced and no observable reaction on either the steering wheel position or acceleration charts indicates where the fault occurred. The video recording of this test does verify that the fault was detected and the secondary steering electronics switched into the UNISTIK™ system when the open circuit fault was switched into the tachometer signal line.

3.1.1.7 Microprocessor Watchdog Failure

The microprocessor reset switch was pressed to simulate a watchdog failure. The chart recording made during this test (Figure C-43) showed that nothing happened to the control system when this was done. The only thing that occurred when the reset was pressed was that the system failure light lit up on the message center. This was a normal response.

3.1.2 Deceleration

The data described in this section, and succeeding brake fault tests, are the second set of data taken after correction of software and hardware problems which surfaced during the first test series.

3.1.2.1 Brake Power Amplifier Power Loss

Figure C-44 shows the results of this test. The fuse was removed from the brake power amplifier during deceleration from 30 miles per hour. This caused the brakes to be released for 0.75 seconds before the secondary brake servo electronics were switched in and re-applied the brakes. The brake application returned to the level similar to that being held prior to the fault insertion within 1.1 seconds of the fault initiation. Except for the delay, the deceleration proceeded normally.

3.1.2.2 Brake Power Amplifier Command Failure

- Test (a) - 5 volts

Figure C-45 shows the chart recording for the first test in this series, namely for a 5 volt DC voltage switched into the brake power amplifier command signal. When this signal fault was initiated, the fault signal was about 1.4 volts different from the brake signal being applied before the fault. The error signal generated was insufficiently large to quickly trigger the switchover to the secondary brake servo circuit. Since there was still a brake signal, however, the vehicle continued to slowly decelerate, but not as rapidly as before the fault introduction. Since greater deceleration was required to stop the vehicle within the desired distance, the driver slowly applied further joystick control. After a delay of approximately 1.2 seconds from the time of fault insertion, the error signal became large enough to be detected and the switchover to the secondary system was accomplished. When this happened, the joystick had been previously moved to demand more brake application. The secondary system applied the brakes a little harder, causing in turn a slightly higher deceleration rate for the remainder of the deceleration maneuver.

- <u>Test (b) - 3 volts</u>

Figure C-46 shows the chart recording for this test. When the brake amplifier command was switched to 3 volts DC during the deceleration maneuver, the brakes were momentarily released. Once the secondary servo electronics were switched in the brakes were then re-applied. The total time the brakes were released before re-application was initiated was 0.1 seconds. The total time from initial fault application until the brakes had been re-applied to their former pre-fault level was 0.45 seconds. Once the brakes returned to their pre-fault level, smooth deceleration continued until the vehicle stopped normally.

- <u>Test (c) - 7 volts</u>

When the 7 volt fault was switched into the brake power amplifier command signal (see Figure C-47), the amplifier command signal increased in the direction of more brake application. For this reason, the brakes were immediately applied harder, abruptly stopping the vehicle. The fault was sensed by the microprocessor. It required 1.5 seconds and also required the joystick to be relaxed (from the pre-fault level) before the error was large enough to detect.

Since braking was being accomplished before the fault was inserted and the fault drove the signal towards additional braking, the lack of sensing of the fault would not have prevented stopping, but only increased the abruptness of the deceleration.

- <u>Test (d) - 0 volts</u>

The response of the UNISTIK™ following insertion of the 0 volt fault is shown in Figure C-48. The result was similar to the result with the 3 volt fault. The brakes were released momentarily then re-applied after the secondary circuit switched in. The time required to re-apply the brakes after fault initialization (0.4 seconds) was nearly the same as the 3 volt fault (0.45 seconds). Once the brakes had been re-applied, deceleration continued normally.

- <u>Test (e) - 12 volts</u>

Figure C-49 shows the results of this test run. The response of the system during insertion of the 12 volt DC fault in the brake power amplifier command line caused the brakes to be applied harder. However, this time, the error signal was large enough to be quickly sensed by the microprocessor, and the secondary circuit switched in after a delay of 0.1 seconds. Since the secondary brake servo electronics are linear in response, and the primary servo is nonlinear (i.e., square function), the new application of brakes was at a slightly different, or higher level, than before fault initiation. This compensated by a slight release of the joystick and a smooth deceleration continued, as shown on the fore-aft deceleration chart.

3.1.2.3 Brake/Throttle Joystick Signal Failure

• Test (a) - 0 volts

When 0 volts were switched into the joystick signal line (see Figure C-50), the servo assumed the throttle had been applied hard. The brakes were immediately released and the throttle momentarily applied, for less than 0.1 seconds, before the secondary brake servo system was switched in. A total of 0.4 seconds were required for the brakes to be re-applied to the stable level to complete deceleration. The throttle was disabled at the same time the secondary brake system was switched in.

• Test (b) - 12 volts

Figure C-51 shows the result of this test. When 12 volts DC were applied in place of the normal joystick signal, the brakes immediately started to be applied harder. The switchover to the secondary brake circuit was very rapid, requiring about 0.05 second. Braking then proceeded normally.

• Test (c) - open curcuit

When the open circuit was applied to the brake joystick signal line (see Figure C-52), the UNISTIK™ system released the brake function and the joystick signal indicated that throttle had been applied, so the throttle was applied. The secondary brake servo circuit switched in after less than 0.05 second, re-applying the brakes, which in turn, responded to their pre-fault level of application in a total of 0.4 second. The throttle was also disabled rapidly. The vehicle completed its deceleration in a normal fashion.

3.1.3 Emergency Stop

3.1.3.1 Brake Power Amplifier Power Loss

For this test, the fuse for the brake power amplifier was removed, during an emergency stop maneuver (see Figure C-53). The microprocessor sensed the fault quickly and switched in the secondary brake servo electronics. After fault initiation 0.2 seconds were required to re-apply the brakes with the secondary circuit, and continue the rapid deceleration.

3.1.3.2 Brake Power Amplifier Command Failure

• Test (a) - 5 volts

During this test, the 5 volt DC fault was inserted 0.5 seconds after the brake application began, forcing the brake power amplifier command signal to that level (see Figure C-54). The fault forced the brakes to be released momentarily. At 0.15 seconds after the fault was initiated, the secondary brake servo electronics switched in and full brakes were re-applied 0.6

seconds after fault initialization. The emergency stop was then continued. The delay in deceleration caused by the fault accounts for the vehicle traveling less than 26 additional feet (at 30 miles per hour) before stopping.

• Test (b) - 3 volts

Figure C-55 shows the results of this test. During the emergency stop, the 3 volt DC fault was switched in to the brake power amplifier command line. This fault caused the brakes to release. The secondary circuit switched in and the brakes were re-applied 0.20 seconds after the brakes were released. The brake servo returned to its level prior to the fault initialization in 0.65 seconds.

Vehicle response was similar to the 3.1.3.2 test, in that the brakes momentarily released then were fully re-applied to lock the wheels and cause the completion of the emergency stop.

• Test (c) - 7 volts

The 7 volt DC fault applied to the brake power amplifier command simulates a full brake application signal (see Figure C-56). For this reason, the brakes, being fully applied, stayed fully applied, and no changes in the vehicle response were noted. The fault did not cause switchover to the secondary circuits until after the stop was completed and the throttle was pressed again. This condition occurred because the error voltage was essentially the same as the correct voltage required for this particular maneuver.

• Test (d) - 0 volts

Figure C-57 shows the chart recording of this test data. When the 0 volt DC fault was switched into the brake power amplifier command signal, the brakes were released momentarily and the throttle activated. Within 0.05 seconds, the throttle was de-activated and secondary brake switched in. To complete the emergency stop, 0.65 seconds was required for the brakes to be fully re-applied.

• Test (e) - 12 volts

This error signal applied to the brake power amplifier command line caused a very small perturbation of the brake application. The fault was sensed and the switchover to the secondary brake servo electronics and re-application of full brakes took 0.15 seconds. Figure C-58 illustrates these results. The emergency stop was performed with essentially no variation from that of a no-fault condition.

3.1.3.3 Brake/Throttle Joystick Signal Failure

• Test (a) - 0 volts

Figure C-59 shows the results of this test. When this error signal was switched into the brake/throttle joystick signal line during the emergency stop maneuver, the brake was released and the throttle was initially activated. Less than 0.1 seconds later, the secondary brake servo switched in and full braking was returned within 0.3 seconds. The throttle was deactivated in less than 0.05 seconds.

- Test (b) - 12 volts

During this test (see Figure C-60), the error signal was in the same direction as a normal braking signal, but to a higher voltage. For this reason, the brakes remained "locked up" upon activation of the fault and the emergency stop continued. During the fault the brake servo never relaxed sufficiently to cause any decreased deceleration (see accelerometer chart).

- Test (c) - open circuit

The open circuit of the brake/throttle joystick signal during an emergency stop had the same effect as the 0 volt failure (see Figure C-61).

3.2 HIGH SPEED TESTS

3.2.1 Lane Maintenance

3.2.1.1 Steering Power Amplifier Power Loss

Figures C-62 and C-63 show the results of these tests at 40 miles per hour and 55 miles per hour respectively. The results at both speeds were similar. When the steering power amplifier fuse was removed during the test run, to simulate power loss, there were no apparent reactions from the steering feedback signals and no observable effect sensed by the driver. On the 40 miles per hour test there was a sight perturbation of the steering power amplifier command signal, the only observable effect in either test.

3.2.1.2 Steering Power Amplifier Command Failure

During tests at low speed where this type of same failure was simulated, the failure mode (i.e., error voltage) which created a significant effect was the 12 volt error. The high speed tests show similar characteristics. In this series of tests the 12 volt error is representative and is shown in Figures C-64 and C-65 for 40 miles per hour and 55 miles per hour respectively. As shown in the figures, a slight perturbation of the steering feedback signal was observed but not enough to require any correction. The video recordings indicated a small (approximately 5 degree) steering wheel rotation, but this caused no reaction from the driver. It appears that straight driving causes the least perturbations during a failure occurrence. During turning maneuvers, the effects are more noticeable. This is verified by results of test series 3.2.2.

3.2.1.3 Steering Power Amplifier Command Offset Voltage Failure

When the small offset voltage error was switched into the steering servo operational amplifier, the steering amplifier command error created was approximately 2.0 volts magnitude (see Figure C-66). This caused the secondary servo electronics to be switched in within approximately 0.1

seconds. No discernable effects were noticed by the driver, or were seen on the steering feedback signal, acceleration curves, or the video recording. The curve for the 55 miles per hour test is shown in Figure C-66. The results at 40 miles per hour were identical.

3.2.1.4 Steering Joystick Signal Failure

For comparison, the results of all six tests in this series are shown in Figures C-67 through C-72. The most interesting results of this test series are shown by comparing test 3.2.1.4a with 3.2.1.4d. The chart recordings for these two tests are seen in Figures C-67 and C-70 respectively. In both cases, the same fault is simulated, namely, a 0 volt signal applied to the steering joystick signal line. The difference is in the vehicle speed during the test. The first test was run at 40 miles per hour, the second test at 55 miles per hour. In test (a), the steering wheel rotated about 15 degrees between the time the fault was initiated and the time the secondary circuit was switched in to correct the perturbation. In the second case (test d), the steering wheel rotation was negligible and hardly noticeable on the video recording. In each case from a hardware signal standpoint, there should have been no difference at the time the fault was initiated. The difference appears to be in the time it took the UNISTIK™ system to sense the error and switch in the backup system. Depending on where the software algorithm that senses time variations is in its operational multi-tasking cycle when a fault occurs, must account for the time variation.

In the worst of the cases for this series (test a), a slight correction with the joystick was required by the driver, but no vehicle control problems resulted from the fault.

The remaining fault voltages tested in this series, at both speeds, caused far less reaction than test (a). The largest wheel motions observed during the remainder of this test series was less than 5 degrees of wheel rotation. In all cases, the largest wheel rotation was observed at the 40 miles per hour speed.

3.2.1.5 Steering Feedback Signal Failure

The results of this test, during the initial test run series, were totally different from the corresponding failure tests at low speed. Figure C-73 shows the result of the first test (a) in this series. This test used a 0 volt signal as the fault voltage applied to the steering feedback signal. When this error voltage was switched into the steering feedback signal line, the steering wheel started to rotate until the fault was removed and steering corrections made to get the vehicle back on the road and under control again.

The cause of this unique response from the UNISTIK™ system was the fact that the computer properly and quickly sensed the fault but then stopped in its software execution before switching in the backup system. This cause was verified by the rapid appearance of the steering failure light and by the video recording. It has been hypothesized that a software fault was to blame.

The software fault may have been due to software corruption due to low voltage on the processor circuits or to an actual program fault. No further tests in the 3.2.1.5 series were run at the time the software fault was detected.

This test series was re-run after power supply improvements and software changes were incorporated.

The results of the re-run of test 3.2.1.5(a) and tests 3.2.1.5(b) through (f) are shown in Figures C-74 through C-79. The results of this series of tests, with the improved power supply and software, were comparable to that of test series 3.2.1.4 (test a). The 0 volt fault signal caused approximately 15 degrees of wheel rotation at 40 miles per hour. The rotation was retraced back to its original position within approximately 0.15 seconds, and no corrective action was required by the driver. At 55 miles per hour (test d), the wheel rotation was about 10 degrees, and again, no corrective action was required. The remaining tests in this series caused less than 5 degrees rotations and no corrective actions. The fault detection and switchover task was typically accomplished in 0.1 seconds.

3.2.1.6 Tachometer Signal Failure

Figures C-80 and C-81 show the results of an open circuit in the steering tachometer circuit. The first figure shows the result at 40 miles per hour and the latter at 55 miles per hour. Also shown on these figures is the chart recording data for tests 3.2.2.6(a-b). Because no fault from a tachometer signal failure was detected during straight-lane maintenance driving, the lane change maneuver was performed right after the first test to see if the fault would be detected then. The fault was correctly detected.

Not only was no fault detected by the failure of the tachometer signal during lane maintenance driving, but also no observable effect was detected. This is due to the fact that the tachometer signal does not exist unless the steering wheel is in motion.

3.2.2 <u>Lane Changing</u>

3.2.2.1 Steering Power Amplifier Power Loss

During the lane change maneuver, the fuse was removed in the steering power amplifier. Figures C-82 and C-83 show the results of these tests at 40 miles per hour and 55 miles per hour respectively. The charts indicated a slight change in the steering amplifier command at the time the faults were initiated, but no effects were noticed by the driver, and no corrections were necessary.

3.2.2.2 Steering Power Amplifier Command Failure

In this series of tests, the results of any specific test run were somewhat dependent upon the exact steering wheel orientation, joystick position at the time of fault initiation and time of secondary circuit switchover.

• Test (a) - 5 volts, 40 mph

In test (a), as shown in Figure C-84, when the 5 volt DC signal was switched into the steering power amplifier command line, the command signal was already close to the 5 volt level. The steering wheel stayed in its position until the error had been sensed and the secondary circuit switched in. The switchover took 0.8 seconds from the time of fault initiation.

During the time of delay of the switchover to the secondary circuit, the driver was pressing the joystick toward the direction of desired turning to return the vehicle to the normal traffic lane. By the time the switchover occurred, a large error was built up between the steering position and that called for by the joystick position. When the switchover took place, the steering wheel immediately rotated approximately 90 degrees to the left to seek the new position called for. This response required, in turn, driver response to compensate for the rapid steering change. The lateral acceleration was larger than for the typical lane change maneuver. Correction requirements were not excessive, and control of the vehicle was not lost during this fault introduction and recovery.

• Test (b) - 3 volt, 40 mph

Figure C-85 shows the chart recording of the test results when 3 volts DC was switched into the steering power amplifier command line. In essence, no discernable effect was observed by the driver, nor indicated on the chart recordings. The major reason for the difference in response for this error introduction and the previous error voltage is that, in this case, the error was large enough to result in a very rapid switchover to the secondary circuit. The faster the error detection and switchover, the less perturbation observed by the system during the lapse of time between fault introduction and system switchover.

• Test (c) - 7 volts, 40 mph

When 7 volts DC was switched into the steering power amplifier command line, the steering wheel rotated slightly (approximately 5 degrees). This rotation is barely noticeable on the steering feedback signal, as shown in Figure C-86. The driver barely perceived the rotation which caused no problem or correction. Again this is because of the large error created which, in turn, created a rapid switchover (less than 0.1 seconds).

• Test (d) 0 volts, 40 mph

Figure C-87 shows the effect of the 0 volt DC signal switched into the steering power amplifier command line. In this case, the steering wheel rotated approximately 20 degrees during the error detection and switchover time period of 0.2 seconds. This amount of wheel rotation required a small correction by the driver by the joystick, once the secondary circuit had been switched in.

• Test (e) - 12 volts, 40 mph

The large error created by the 12 volt DC signal application caused a rapid secondary circuit switchover (see Figure C-88). No discernable effect was detectable on the charts. The switchover occurred in less than 0.1 second.

• Test (f) - 5 volts, 55 mph

Figure C-89 shows the results of this test, using a 5 volt fault signal. The system required 0.8 seconds to switch to the secondary circuit after introduction of the fault. Since the command signal was close to the 5.0 volt level prior to introduction of the fault, there was essentially no steering wheel response during the time of the fault. During the time the fault signal was preventing any motion of the steering wheel, the joystick was being moved in an effort to direct the vehicle to regain the driving lane. Once the switchover occurred, the steering wheel responded to the new joystick position and immediately rotated approximately 20 degrees. This required minor corrective response from the driver, by the joystick, but was easily accommodated.

• Test (g) - 3 volts, 55 mph

Figure C-90 shows the results of this test. There was no discernable effects when the 3 volt DC signal was switched into the steering amplifier command line. Again, this is due to the relatively large error signal which was created which, in turn, caused rapid fault sensing and switchover to the secondary circuit.

• Test (h) - 7 volts, 55 mph

The results of this test are essentially the same as at 40 miles per hour. A small (less than 5 degree) steering wheel rotation was experienced, but required no corrective response from the driver. The switchover to secondary circuit was very rapid. Figure C-91 shows these results.

• Test (i) - 0 volts, 55 mph

Figure C-92 shows some steering feedback signal perturbation at the time of initiation of the 0 volt fault signal into the steering power amplifier command line. This represents some steering wheel rotation. The video recording verified that the steering wheel rotated a small amount, approximately 15 degrees, before the secondary circuit was switched in. Minor correction was required by the driver to compensate for the fault-induced wheel rotation.

• Test (j) - 12 volts, 55 mph

The large error created when the 12 volt DC signal was switched into the steering power amplifier command line, caused a very rapid switchover to the secondary circuit. There was a small, perceptible reaction which can be seen on the steering feedback signal, shown in Figure C-93. Minor driver correction was required.

3.2.2.3 Steering Power Amplifier Command Offset Voltage Failure

The two tests performed in this series, at 40 and 55 miles per hour, showed the same results, as seen in Figures C-94 and C-95. When the small offset voltage was switched into one of the steering servo operational amplifier inputs, the command signal was offset by approximately 2.0 volts, which caused a rapid switchover to the secondary circuit and no discernable effect on the steering.

3.2.2.4 Steering Joystick Signal Failure

The results from this series of tests were similar to the previous series in that the results varied, depending upon the steering wheel position, joystick position, and software operation condition at the time the faults were initiated. These differences masked the individual differences caused by the different fault voltages used during the tests. This is most obvious when comparing the same fault voltage results at the different vehicle speeds. Overall, the performance results are indicative of what would be expected in an actual failure situation.

- Test (a) - 0 volts, 40 mph

Figure C-96 shows the results when 0 volts DC was switched into the steering joystick signal line at 40 miles per hour vehicle speed during a lane change maneuver. As seen from the charted signals, no observable effect was created by the fault. Tbe video recording verified that switchover to the secondary circuit was very rapid, and accounted for the minimal perturbations caused by the fault introduction.

- Test (b) - 12 volts, 40 mph

When 12 volts DC was switched into the steering joystick signal line, the delay which resulted before the secondary circuit switched in caused the steering wheel to rotate approximately 30 degrees before the changeover occurred. The driver made small corrections to compensate for this perturbation, once the secondary circuit engaged, but significant problem in control were created. The error detection and switchover cycle took approximately 0.2 seconds for this test (see Figure C-97).

- Test (c) - open circuit, 40 mph

The results of this test were only a perceptible perturbation in the steering wheel rotation, as shown in Figure C-98. No abnormal steering corrections were made by the driver. The switchover to secondary circuit was very rapid (less than 0.1 seconds).

- Test (d) - 0 volts, 55 mph

This test yielded different results than the one at 40 miles per hour in that there was nearly 10 degrees of steering wheel motion, as shown in the steering feedback signal (Figure C-99). This occurred when the fault was switched in and before the secondary circuit switched in (approximately 0.1 seconds later). A small steering correction was made by the driver to compensate for this response, but no driving problems were caused.

- Test (e) - 12 volts, 55 mph

Figure C-100 shows that there was no discernable steering reaction to the 12 volt fault which was switched in for this test. The video recording shows a barely perceptible reaction of the steering wheel at the time of fault initiation.

- Test (f) - open circuit, 55 mph

The result of this test (shown in Figure C-101) is essentially the same as test (e) with 12 volts, 55 mph, except slightly more steering wheel reaction was observed on the video recordings (approximately 5 degrees). No driver reaction was required, however.

3.2.2.5 Steering Feedback Signal Failure

No tests were performed for this test series during the initial testing because of the dangerous results seen during the first test 3.2.1.5. This test series was performed after UNISTIK™ modifications were completed. Figures C-102 through C-107 show the results of these tests. The results are nearly identical with the second test series 3.2.1.5. The 0 volt failure at 40 miles per hour exhibited the maximum wheel rotation during the fault. It was approximately 10 degrees of rotation and required no control compensation. All other tests in this series were less significant.

3.2.2.6 Tachometer Signal Failure

The results of these two tests can be seen by referring to Figures C-80 and C-81. When the open circuit was inserted in the tachometer signal line during a lane change maneuver, some steering wheel reaction was observed at both speeds with the largest reaction occurring at 55 miles per hour. The steering power amplifier command signal showed a peak-to-peak reaction of nearly 2.0 volts at 40 miles per hour. The steering feedback signal indicated that the steering wheel rotation was approximately 50 degrees peak to peak, or 25 degrees peak reaction during recovery from the fault. This was caused by the driver, during correction by the joystick after the fault was switched in.

At 55 miles per hour, the results were similar except larger corrections were experienced. A 90 degrees peak steering wheel rotation was required by the driver during the corrective maneuvers by the joystick, after the fault was switched in.

During both tests the driver never lost control of the vehicle.

3.2.3 Deceleration

3.2.3.1 Brake Power Amplifier Power Loss

The results of this test series were essentially identical at 40 miles per hour and 55 miles per hour (see Figures C-108 and C-109). During a deceleration maneuver, the brake power amplifier fuse was removed, creating the power loss fault. This action momentarily released the brakes, but the fault was sensed. The secondary brake servo circuit switched in, and the brakes re-applied to their pre-fault level within 0.4 seconds after initialization of the fault. After the brakes were re-applied, the deceleration continued normally, except at a slightly higher rate, as shown in the deceleration recordings.

3.2.3.2 Brake Power Amplifier Command Failure

- Test (a) - 5 volts, 40 mph

When 5 volts was applied to the brake power amplifier command line during a deceleration from 40 miles per hour, the voltage difference between the fault voltage and the pre-fault voltage on the command line was approximately 1.0 volt. The error was not sufficiently large to be sensed by the software algorithm. Once the fault was initiated, the vehicle ceased to decelerate. The driver increased the brake joystick signal until the joystick signal created a sufficiently large difference between the faulted brake signal and the one called for by the joystick, then a fault was sensed and the secondary circuit switched in. This process took 2.7 seconds. Once the secondary circuit switched in, the brakes were applied hard, to the level called for by the joystick signal, and rapid deceleration completed the stopping maneuver. Figure C-110 shows the chart recordings for this test.

- Test (b) - 3 volts, 40 mph

In this test, the 3 volt DC fault signal was in the direction of applying throttle, so the error signal was large enough (1.5 volts) to be detected. During the deceleration, when the fault voltage was switched in, the brakes momentarily released, but then the secondary servo circuit was switched in after 0.2 seconds and the brakes re-applied to their pre-fault level within 0.45 seconds (see Figure C-111). The deceleration maneuver continued normally from this point.

- Test (c) - 7 volts, 40 mph

Figure C-112 shows the results if this test, where a 7 volt DC fault signal was switched into the brake power amplifier command line during deceleration from 40 miles per hour. The error voltage caused additional (harder) brake application. Within 0.5 seconds after the fault was initiated, the secondary electronics had switched in and the deceleration continued. During the existence of the fault, the driver reduced the brake joystick position and signal, so that when the secondary circuit switched in, the brakes released somewhat. The driver continued to adjust the brake joystick position to continue deceleration until the vehicle stopped.

• <u>Test (d) - 0 volts, 40 mph</u>

During deceleration, when 0 volts was switched into the brake power amplifier command line, the brakes were momentarily released, but the fault was quickly sensed. The secondary circuit switched in and from the time the fault was created the brakes re-applied to their pre-fault level within 0.5 seconds. Figure C-113 shows these results. After the secondary circuit switched in, the deceleration continued normally.

• <u>Test (e) - 12 volts, 40 mph</u>

Figure C-114 shows the results of this test. When the 12 volt DC fault signal was switched in during the deceleration run, the brakes were initially applied harder. The fault was sensed within 0.1 seconds and when the secondary circuit was switched in the brakes again came under control of the brake joystick. The deceleration continued normally from this point, except at a slightly more rapid rate called for by the secondary brake servo. This was due to the differences between the nonlinear and linear modes on the primary and secondary brake servo electronics respectively.

• <u>Test (f) - 5 volts, 55 mph</u>

Figure C-115 shows that the results of this test were very similar to those of test (a) with 5 volts, 40 mph. The difference was that the initial signal levels, prior to the fault introduction, and the changes in the joystick position after fault introduction, allowed the error to be sensed sooner (1.5 seconds). The secondary circuit switched in allowing the deceleration to continue normally.

• <u>Test (g) - 3 volts, 55 mph</u>

The results of this test were essentially the same as test (b), 3 volts, 40 mph. Differences were in the driver's control of the joystick during the total deceleration maneuver, and how long the brake was held on after the vehicle stopped. Figure C-116 shows these results.

• <u>Test (h) - 7 volts, 55 mph</u>

The result of this test at 55 miles per hour were identical to those seen at 40 miles per hour. Figure C-117 shows the test results for this test.

• <u>Test (i) - 0 volt, 55 mph</u>

Figure C-118 shows that the results of this test are similar to test (d), 0 volts, 40 mph, for the same fault introduction, except that the error was detected and brakes re-applied in 0.3 seconds, rather than 0.5 seconds.

• <u>Test (j) - 12 volts, 55 mph</u>

This test showed results similar to test (e), 12 volts, 40 mph, except that 0.4 seconds were required for the error to be sensed and the switchover to the secondary circuit made. This is shown in Figure C-119. The deceleration continued normally after switchover to the secondary circuit.

3.2.3.3 Brake/Throttle Joystick Failure

- <u>Test (a) - 0 volts, 40 mph</u>

Figure C-120 shows the result of this test. During deceleration when 0 volts DC was applied to the brake/throttle joystick signal line, the brakes were initially released and the throttle activated. The error was sensed and the secondary brake servo electronics switched in and the braking returned to its pre-fault level within 0.4 seconds of the fault introduction. The throttle failure was also sensed, and the throttle was shut off by the monitoring microprocessor.

- <u>Test (b) - 12 volts, 40 mph</u>

Figure C-121 shows the results when 12 volts DC was switched into the brake/throttle joystick signal line. The error was sensed rapidly and the secondary circuit switched in within 0.05 seconds. The deceleration continued normally, from this point.

- <u>Test (c) - open circuit, 40 mph</u>

When the open circuit was switched into the brake/throttle joystick signal line, the circuit voltages were driven in a similar fashion to when a 0 volt signal was applied, as in test (a), 0 volts, 40 mph. The brake was momentarily released and re-applied as the secondary circuit was switched in. The brakes returned to their pre-fault level within 0.4 seconds after the initial fault occurred. The throttle was also applied, but the throttle fault was detected and the throttle shut off immediately. Figure C-122 shows these test results.

- <u>Tests (d-f)</u>

This test series had results shown in Figures C-123 and C-125. They are very similar to the results of the same fault introductions at 40 miles per hour. The minor differences were caused by slight differences in initial joystick position prior to fault application, and joystick position changes after the secondary brake switched in.

Section 4

VANCOUVER TRIP ROAD TEST

4.1 FIRST DAY - JULY 15, 1986

The first day of the Vancouver trip provided an opportunity for the drivers to become used to driving the UNISTIK™ system/vehicle for extended periods at highway speeds. A total of 432 miles were driven this day (all but three miles were driven with the UNISTIK™). There was a strong crosswind blowing from left to right across the vehicle's path the entire day. Because the van vehicle is affected significantly by crosswinds, driving was more difficult. Steering corrections were continuously required to compensate for the variable forces affecting the direction of travel.

Figures C-126 through C-128 show chart recordings made during the morning of July 15th, while the vehicle was being driven with the UNISTIK™ system. Figures C-126 and C-128 plot vehicle speed, brake/throttle joystick, steering feedback and steering joystick signals. The first recording was at a speed of 45 miles per hour and the second at a speed of 55 miles per hour. These figures show the cyclical nature of the driver's response on the steering joystick to maintain the vehicle in a straight-lane driving condition.

In Figure C-126 the most prominent cyclical pattern averaged 33.5% (peak) of full joystick travel with cycle times which varied from 2.7 seconds per cycle to 13 seconds per cycle. The average time was approximately 5.7 seconds per cycle.

In addition to the major cyclical pattern, the figures show a smaller magnitude, higher rate cyclical pattern superimposed upon the major pattern. This smaller pattern had peak excursions of 4.5% of full joystick travel, but with the much higher rate, on the order of 0.7 to 0.8 seconds per cycle.

It is also apparent that there is a left directed bias in the average joystick position. In Figure C-126 this amounted to a level of 7% of peak steering joystick travel. This value is apparently a function of both the crosswind and a slight steering misalignment in the vehicle's mechanical steering system. It does not appear to be caused by the UNISTIK™ system.

The cyclical steering control movements are greatly reduced by the nonlinear response of the steering system which determines the actual steering movements. The steering feedback signal shown in Figure C-126 and the video recordings taken at the same time show that the actual steering position cyclical motions appear to be typically 3% to 5% of full travel (20 to 30 degrees of steering wheel rotation).

It is interesting to note, as shown in Figure C-128, that at the higher speed of 55 miles per hour the peak steering joystick excursions were reduced to 18% of full joystick travel.

Figure C-127 shows a chart of some of the UNISTIK™ system voltages. The logic and primary 12 volt voltages appear to be very stable as the vehicle is being driven. The battery voltage varied approximately 3% as the system performed during driving.

The monitoring microprocessor created some fault signals on the message center. After about 80 miles had been driven this first day, the message "pull back joystick" appeared, just after the vehicle was driven off the freeway onto surfaced streets in Cheyenne, Wyoming. The vehicle was stopped, the UNISTIK™ system restarted, and the message did not re-appear. When this failure occurred, there was a CRT terminal hooked up to the microprocessor, but the terminal was turned off. The terminal was disconnected from the interface cable, with the thought that this connection may have created a noise spike . This particular message response never re-occurred during the trip. The UNISTIK™ system continued to function during the time this message had appeared on the message center.

Late in the morning, another message appeared on the message center. This message was "secondary steering position error". No problem was apparent with the UNISTIK™ system, and the system continued to work properly. The vehicle was stopped, and the UNISTIK™ system restarted, with no re-occurrence of the message at that time. At the time the message occurred, the air conditioning unit heat exchanger in the vehicle had just frozen and the unit had to be shut off. It was questioned at the time if a possible voltage transient from the air conditioning unit could have caused the erroneous message to appear.

Once during the day the vehicle was stopped for a time. When the driver returned to the vehicle the brake lights were on. Apparently, the brake pedal had not released quite far enough to be certain that the brake light switch would not be activated. When this happened, a slight tug on the brake pedal released the brake light switch. It is probable that occasionally the friction in the brake servomechanism prohibits the brake pedal in returning all the way back to a full release point.

During the afternoon of July 15th, a second series of chart recordings were made. Figure C-129 shows a section of these charts. The steering joystick signal is the most interesting on this chart. A lower average peak major steering correction magnitude was seen (to approximately 31% from 33.5%). The left steering bias was also less, down to 4.5%. It is apparent that road conditions as well as crosswinds affect the steering conditions.

4.2 SECOND DAY - JULY 16, 1986

There were a total of 484 miles driven on the second day (all but one mile being driven with UNISTIK™). The crosswinds had diminished considerably. The driver's comment, after driving only a few minutes, was "its a lot easier today". Figure C-130 shows a chart taken during the morning while driving. The steering joystick signal showed a marked difference from the previous day's data. The peak joystick excursions to maintain course dropped to typically 14% of total joystick travel, and the steering feedback signal changes (representative of steering wheel rotation) reduced accordingly. The rate of correction motions increased, but the incidence of the small, high frequency corrections decreased. The major correction motion rate averaged about 3.0 seconds per cycle.

During the afternoon another chart was run while the vehicle was driven through a rain storm. The chart showed some increase in joystick motion peak levels and a decrease, once again, in the rate of corrections. The wind had somewhat increased during the rainstorm and probably accounted for some of the change. This chart is shown in Figure C-131.

As perceived by the drivers, driving with the UNISTIK™ system during the rain storm caused no noticeable differences in driving requirements.

During the second day, there were three occurrences of the appearance of the "secondary steering position error" message on the message center. Each time they occurred, the system was shut off and restarted. The message did not immediately re-occur.

There was a re-occurrance of the condition where the brake light stayed on when the system was shut off. Pulling up slightly on the brake pedal allowed the light to go off.

While the driver was performing a turn-about at Billings, Montana, the "steering warning" and "system failure" messages appeared on the message center. No other error messages were seen at that time. The system was re-started and the phenomenon did not re-occur. The tendency exists during tight maneuvers, especially when both steering and brake servos are activated simultaneously, for these messages to appear. The lowering of system power supply voltages due to the heavier load on the supply and extra voltage drop in the cabling because of the higher current could explain this.

4.3 THIRD DAY - JULY 17, 1986

On the third day, 482 miles were driven, all with UNISTIK™. Figures C-132 and C-133 show samples of the morning and afternoon data recordings from the third day of the trip. There appear to be no significant differences between these and those of the second day. It should be noted that both drivers have chart recordings which are very similar. In general terms, while driving, smaller peak steering corrections correspond with a more rapid rate of the corrections. For the afternoon recording, the typical correction magnitude is about 14% peak with a rate of about 2.0 seconds per cycle.

The "secondary steering position error" occurred four more times on the third day of the trip. In each case, the system was re-started without an immediate re-occurrence. It should be noted that in most, but not all cases, these occurrences happened within 10 to 20 minutes after the system was first started after some period of being shut off. A system voltage recording was being made when one of the error messages occurred. This chart is shown in Figure C-134. There is no evidence indicated on this chart that any "glitch" occurred on the logic power. There are the normal variations occurring on the battery voltage of the system.

One time as the chart recordings were completed, and the inverter was switched off, a "system failure" message was shown on the message center within 2.0 seconds after the inverter was shut off. The system was re-started and the message did not re-occur.

A final incident occurred on the third day. At the end of the day's travel, in a subdivision in Seattle while driving on winding, hilly roads, a buzzing noise occurred for about 2 seconds. It sounded like it came from under the steering column in the area of the servomechanisms. It felt to the driver that it was in the steering servo system. The system continued to be controllable by the joystick during the incident, and the incident ceased without the system having to be re-started. When the vehicle was again driven later in the evening, the problem did not reoccur.

4.4 FOURTH DAY - JULY 18, 1986

Only 123 miles were driven with the UNISTIK™ system on this day because the UNISTIK™ system was not used while driving in Canada. No incidences of erroneous messages occurred on this day, and no chart recordings were taken.

4.5 FIFTH DAY - JULY 26, 1986

The UNISTIK™ system was used for all 374 miles driven this day. Figure C-135 shows a sample of data recorded on the morning of July 26th. This was recorded while the vehicle was being driven over winding roads on Whidbey Island. The speed was much lower (35 to 45 miles per hour) most of the time. The chart recordings show the increase in activity on the steering and brake/throttle joysticks for this type of driving. No problems were experienced by the driver during this type of driving.

Figure C-136 shows a second chart recording taken during the morning of July 26th. This one was during freeway driving in heavy traffic on the outskirts of Seattle. There was no additional driving difficulty due to this type of driving.

There were no occurrences of erroneous messages on the message center this day.

4.6 SIXTH DAY - JULY 27, 1986

All but eight of the 509 miles driven on the sixth day were driven with the UNISTIK™. The morning data recordings for the sixth day were taken on a winding road at speeds of 35 to 45 miles per hour (see Figure C-137). These data appear similar to the data taken on similar roads on July 26th. It is interesting to note that the video recordings from this same time period show that the steering wheel usually rotates only about 45 degrees when the vehicle is driven around corners on such winding roads. The chart recordings verify this.

During the afternoon data recording session (see Figure C-138), straight roads were again being driven. It should be noted that the low level, high rate steering corrections were less prominent in this run. Even the larger corrections occurred at lower rates. This is probably indicative of increased driving experience on the part of the drivers.

On two occasions during this day while performing turn-about maneuvers, the UNISTIK™ system acted as if it would not allow full left turn capability, and the "system failure" message appeared. After the first occurrence, the system was restarted and the maneuvering completed. About ten minutes later, when performing a similar maneuver, the same thing occurred. The system was re-started again and no re-occurrence took place the remainder of the day. This condition was later duplicated in Boulder, and determined to be caused by a small delay in the system returning to low speed steering gain from high speed mode. This occurs when making sharp turns after slowing rapidly from above 35 miles per hour.

4.7 SEVENTH DAY - JULY 28, 1986

On the seventh day, a total of 513 miles were driven, five of which were driven manually, the rest with UNISTIK™. The seventh day's morning data recording was taken while the vehicle was driven down a winding mountain road. Figure C-139 shows these data. Speed was 30 to 35 miles per hour. Since it is down hill and curving road conditions, the brake/throttle joystick reflects the frequent braking required to hold the speed down and to brake additionally for the turns. The steering joystick signal reflects the turning required, as well as the normal corrections. The steering feedback signal also reflects the vehicle negotiating the turns.

By this point in the trip, the drivers had considerable experience driving with the UNISTIK™ system, and even this type of driving was not a problem. Much of the driving response had become natural by this time and the drivers automatically compensated for different driving conditions.

During the afternoon's data recording session, the vehicle was again on good, straight roads and nothing of note was evident. No sample of these data is included in this report.

During the morning data run, a chart recording was made of the system voltages. A portion of this chart is shown in Figure C-140. The voltages look stable and compare favorably with those taken on the first day of the trip and charted in Figure C-127.

There were six occurrences of the "system failure" message during this day of the trip. This time, they occurred both during tight, low speed maneuvers and during highway travel. Except in one case, each time they occurred the system was re-started without immediate re-occurrence of the message.

On one of the occasions of the "system failure" message, the buzz was heard from the steering servo system again. In this incident, the "primary steering position error" message was also displayed. This particular occurrence happened right after a re-start had been made from a previous "system failure" message incident.

A second occasion of the "system failure" message on this day happened while leaving a parking place. This time, the throttle was also disengaged. No additional messages were noticed.

Later in the day, there was another occurrence of the same message while the emergency brake was being released. In this case, the "throttle servo error" message also occurred.

No obvious cause was apparent for these conditions which occurred frequently on this day. Possible effects due to power supply variations (especially during startup of the engine) or other software faults could be involved. Some intermittent hardware faults could also have caused some of them, but from day to day they do not seem to be consistent.

4.8 EIGHTH DAY - JULY 29, 1986

On the last day of the trip, 498 miles (all using UNISTIK™) were driven. During the morning of the eighth and last day of the road driving of the Vancouver trip, one data recording run was taken. A sample is shown in Figure C-141. For this run, the rate of corrections on the steering varied much more from time to time. This was probably due to better reaction to actual road conditions, rather than a mechanized response to all conditions. The average rate of major correction was 5.8 seconds per cycle, but the range varied from 2.2 seconds per correction to 14 seconds per cycle. Fewer small, high rate corrections were evident, compared to the first day of the trip. The road conditions were similar to those of the first day and some crosswinds existed, so the results are quite compatible for comparison.

First thing in the morning this day, the weather was very cold (38 degrees). The voltage on the system was too low to allow the disk drive to function. The vehicle engine was started and then the UNISTIK™ software loaded. It should be noted that after this type of startup procedure, there were no erroneous messages during this whole day. These are possible clues to the effects caused by voltage limitations.

4.9 GENERAL COMMENTS ON VANCOUVER TRIP ROAD TEST

Ambient temperature variations did not seem to affect the system performance once the system had been started. The temperature range seen during the trip was from 38 degrees to 85 degrees F.

In general, driving with the UNISTIK™ requires more concentration than manual driving, because of the sensitivity of the controls. However, driving in this manner does not create significantly extra stress or fatigue. Two to three hour driving sessions were regularly driven with relative ease.

The video recordings show that there is some wandering within the driving lane while driving with UNISTIK™. This may be greater than typically found while driving manually. There was no problem in staying within a driving lane boundary.

Even though there were many incidents of error messages generated by the software, no hardware faults have been found which could explain them. This leads to speculation that the reason may be software faults. Some if not all of these software faults may likely be caused by system voltage problems, especially during engine startup. Steps have been taken to further evaluate the software, and correct the power supply limitations.

After the trip the UNISTIK™ vehicle was returned to Johnson Engineering Corporation, and a thorough visual inspection was given to the UNISTIK™ system, with the following results: Due to vibration the screws holding the card cage had worked loose, but were still supporting the card cage. A cold solder joint was found on one indicator lamp in the transmission control housing. Some wear had occurred on the steering wheel where it rubbed against the servo mechanism cover.

There were no apparent wiring problems or loose wires found, nor was there any evidence of gear wear in the servo mechanisms.

Section 5

HANDICAPPED/ABLE-BODIED DRIVER COMPARISON TEST

Figures C-142 and C-143 show two samples of chart recordings made when a C5 quadriplegic briefly drove the UNISTIK™ system on actual roads at speeds up to 40 miles per hour. Figure C-142 was recorded during the first five minutes of the test drive. Figure C-143 was recorded after approximately 15 minutes of test driving.

The steering joystick signal provides the most interesting information. During the first few minutes of driving, and when speeds were being varied, the average rate of the larger fluctuations in the steering signal occurred at 6.25 seconds per cycle. After the 15 minute break-in period, this rate had reduced to 5.67 seconds per cycle. Smaller, higher rate fluctuations also were present, much as they were when an able-bodied driver drove. These smaller fluctuations occurred at a rate of approximately 0.73 seconds per cycle during the first few minutes, and increased to an average of 0.5 seconds per cycle after 15 minutes of driving.

If these data are compared to that taken with an able-bodied driver at the start of the Vancouver trip, it can be recalled that the average rate of the large fluctuations measured at the first day of the Vancouver trip was 5.7 seconds per cycle. This value is very close to the 5.67 seconds per cycle measured after 15 minutes of driving by the handicapped driver.

At the start of the Vancouver trip, the average rate of the lower magnitude fluctuations was about 0.75 seconds per cycle. This is similar to the starting rate for the handicapped driver. His rate after 15 minutes increased to 0.5 seconds per cycle.

The magnitudes of the cyclical responses were quite similar between the handicapped driver and the early recordings from the Vancouver trip. The larger fluctuations were about 35% of peak joystick travel. The smaller excursions were about 5% of peak joystick travel. This compares to 33% and 4.5% respectively, which was measured during the first day of the Vancouver trip.

In general terms, the chart recordings show that there is no large difference between the driving characteristics for the handicapped driver and the able-bodied driver. This is especially true when the differences in the road conditions that existed during the two tests are compared.

Section 6

BENCH TEST RESULTS

The test plan for the bench tests is attached to this document as Appendix B. The following sub-sections summarize the results of each of the three types of tests performed during bench testing.

6.1 TEMPERATURE CYCLE TEST

For this test, the steering servo electronics were placed in a temperature-controlled chamber. The electronics were driven by a separate circuit which supplied proper simulated input signals, and cycled twice from -40°C to +80°C. During these temperature cycles, certain signals within the servo electronics were monitored by a chart recorder.

The test signals generated by the signal simulator were: vehicle speed (high or low), steering tachometer (delayed pulses), steering joystick (square waves), and steering feedback (filtered square waves). Depending on whether the speed signal was high or low, there was a different level for the steering feedback signal. Figures C-144 through C-149 show chart recordings of these four signals for both high and low speed signals, and at the three different supply voltage levels that were used during the test.

The steering feedback signal was used as the reference when charting the other servo signals during the test, rather than the steering joystick signal called for in the test plan. This was because it was indicated by the two different signal levels whether the vehicle speed signal was in the high or low speed mode.

The two servo signals which were monitored closely during the tests were the steering power amplifier output current (into a "dummy load") and the steering power amplifier input command (from the low level servo electronic card). On the same four-channel chart recording, the temperature of the temperature chamber or the power amplifier heat sink were monitored, and the steering feedback signal input to the low level servo electronic card was shown for reference. Figures C-150 through C-152 show samples of these signals: at the three test power supply voltage levels, at the start of the temperature cycle test, before the temperature was changed from ambient. These figures only show the results when the speed signal was "low". For comparison purposes this case is used in the remainder of this report. The speed signal "high" case shows similar results, even though the waveforms for amplifier current and commands are somewhat different for the second case.

The test signals applied to the servo electronics were designed to simulate typical signals that exist in actual driving conditions, not extreme signal conditions.

The power amplifier section of the steering servo electronics was tested without a fan for cooling the power transistor heat sink. It was found during the temperature tests that the heat sink temperature follows closely the ambient temperature (or chamber temperature). The lag in time is due to the thermal mass of the heat sink.

The steering amplifier current signal shown on Figures C-150, and following, is the absolute magnitude of the current. This accounts for the unusual shape of the current waveforms. The overshoots in current shown in the chart are in the same direction as the original current pulse.

The test input signals were specifically designed to create some overshoot in the current response, so that small shifts in offsets and gain changes with temperature could be easily seen.

The lines drawn on many of the charts signals in this section are for the purpose of analyzing the signals for variations with temperature and voltage.

The signals of Figures C-150 and C-152 are very similar. There was very little performance difference between the circuits operating at 12 volts and at 13.4 volts on the power supply. There were distinctive differences at the 10.6 volt power supply level. At the lower voltage, the voltage reference integrated circuits started to loose their voltage regulation, which in turn created problems in the operational amplifier bias voltages, producing the variations in circuit output waveforms.

Figures C-153 through C-155 show the servo electronics signal waveforms (comparable to Figures C-150 through C-152) during the first temperature cycle, when the chamber temperature was stabilized at +80°C.

If Figure C-153 is compared with Figure C-150, the changes which occurred during the change in temperature from +25°C to +80°C can be seen. Note first the steering amplifier command signal. This signal is generated in the low level servo electronic circuit card, and is basically the steering joystick signal minus the steering feedback and steering tachometer signals, with gain and offset adjustments. The first negative going pulse of the command signal does not have, as part of its makeup, the tachometer signal. This portion of the signal is a good indication of only differences in gain and offset between the joystick and feedback signal paths in the low level electronics. The first command pulse in Figure C-153 shows approximately a 15% offset from the center for the decayed level portion of the pulse, compared to that in Figure C-150. This is caused when the two signals (joystick and feedback signals) no longer cancel each other exactly through the low level circuit. This in turn is caused by a relative gain change in the two portions of the circuit with temperature. The relative gain change between the joystick and feedback signal paths is observed to exist on the other pulses of the command signal of Figure C-153.

The resulting offset in the absolute level of the "tail" of the command pulses is what causes, in turn, the major differences in the appearance of the current pulses. The trailing portions of the current pulses are greatly affected by the small changes in the offset from center of the command pulse tails.

The center of the command waveform (as interpreted by the power amplifier input) appears not to change substantially for 12 volt input power when the temperature changed from +25° to +80° . This center of the command waveform or the center reference point for the power amplifier input is determined by the minimum dips in the current waveform, and from there to the voltage level of the command waveform, at the time of these minimums.

If Figure C-154 is compared to both Figures C-153 and C-151, the changes which occurred in the circuits at +80°C, and at 10.6 volts power supply voltage, can be seen. The amplifier command signal did not change significantly from that at 12 volts supply voltage. An analysis of the current waveforms, however, indicates that the amplifier center reference point shifted lower by approximately 10% of the full scale signal output.

Similarly, if Figure C-155 is compared with Figure C-153, it can be determined that the amplifier center reference point raised by about 5% of the full scale signal output.

Figures C-156 through C-158 show the same data with the temperature of the chamber at -40°C. The same analysis was performed on the data at -40°C.

Table C-I summarizes the results of the amplifier center reference changes with voltage at the different temperatures.

TABLE C-I. POWER AMPLIFIER CENTER REFERENCE VOLTAGE CHANGE AS FUNCTION OF TEMPERATURE AND SUPPLY VOLTAGE (percent of full scale amplifier output)

	POWER SUPPLY VOLTAGE		
CHAMBER TEMPERATURE	12 VOLTS	10.6 VOLTS	13.4 VOLTS
+80°C	0%	-10%	+5%
+25°C	REF.	-19%	-1%
-40°C	0%	-29%	0%

The change in relative gain between the joystick and feedback signal paths appeared to change approximately -6% between +25°C and -40°C.

Figures C-159 through C-161 show another set of chart recordings made of the servo signals after the second temperature cycle test had been completed and the temperature of the chamber returned to ambient, at 25°C. It can be seen that these signals are essentially identical to those of Figures C-150 through C-152, which were taken at the start of the temperature cycle test. Therefore, no observable changes occurred in the circuits during the cycle tests.

6.2 EXTENDED HIGH TEMPERATURE TEST RESULTS

For this test, the steering servo electronics were operated in the same manner as in the temperature cycle test. The temperature of the temperature chamber, however, was held at +60°C, and the power supply voltage at 13.4 volts. The test lasted for seven days, with the temperature held continuously at +60°C. The electronics were operated approximately eight hours per day during the work week.

Chart recordings were made approximately every hour during the times the electronics were operating. The data recorded were: chamber temperature, steering amplifier current, steering amplifier command, and steering feedback signal. These are the same signals which were recorded during the temperature cycle tests. A slower chart speed was used on this test (1 mm/sec). Figures C-162 through C-166 are sample charts from the data for this test.

Figure C-162 was taken after the chamber first arrived at the +60°C level and the circuits had stabilized.

The test continued uneventfully from startup until 52 hours had elapsed. A failure then occurred in one of the components in the low level electronics card. There was no advance warning that the failure was about to take place. Figure C-163 shows the chart recording just before the problem occurred. The signals are identical to those at the start of the test.

When the failure occurred, the chamber was returned to room temperature, and troubleshooting was performed to determine the cause. The failure occurred in the +/- 15 volt DC/DC converter module, which supplies power for many of the operational amplifiers in the low voltage circuits. This module was replaced and the chamber returned to +60°C, within two hours of the failure.

Figure C-164 indicates typical waveforms on the signals after the change in the DC/DC converter. There are some differences in the overshoot waveforms in the current signals. This is due to slight variations in the actual voltages generated by the new converter, compared to the old component.

An investigation of the failed component revealed that this particular device was only rated to +60°C operating temperature. It had been subjected to +85°C temperatures while operating during the previous tests, and this apparently weakened the device sufficiently to cause the eventual failure during the "burn in" test. If system operation is desired above +60°C in the production units, then a higher temperature rated component will have to be selected for this DC/DC converter.

Once the test was under way once again, it was continued for the remainder of a total of 168 hours, without additional incident. Figure C-165 shows that the waveforms at the end of the test period are the same as when the new DC/DC converter first been installed. Figure C-166 shows the signal waveforms after returning the chamber to +25°C. Some small changes in waveforms occur with the change in temperature, but this is in line with the results of the temperature cycle tests previously discussed.

6.3 MECHANICAL CYCLE TEST RESULTS

The procedure for the mechanical cycle test is outlined in Appendix B, the Bench Test Plan. During this test, the brake and steering servo mechanisms were cycled to approximate ten years of average driving. The steering was operated from one end position to the other, and the brake was applied without aid of the power assist. This technique placed maximum stress on the mechanical components, especially gearing, in the servo mechanisms.

No failure occurred during this test, and the servomechanisms appeared to operate the same after the test as before. There was, however, slightly more noise generated by the steering servo after the test, compared to pre-test levels. (This increase in noise is subjective only, and was not tested in a definitive manner.)

A visual inspection of the servo mechanisms was made after the test was completed. The brake rack and pinion assembly appeared the same as pre-test conditions. No increased "play" was detected in this mechanism.

In the steering gears, some wear was deetected on the servo motor pinion gear. This gear was exposed to the most stress and usage than any other during the test. The mating gear to the pinion had no detectable increased wear. It is suggested that the increased noise level in the steering is due to this pinion gear wear. The wear manifests itself in a "sharpening" of some of the pinion gear teeth. The gear still appears to have considerable useful life left.

Since there was tooth wear in the steering servo, there is additional "slack" or "play" in these gears, now that the test has been completed.

No other evidence of wear or problems was detected during the inspection. All bearings appeared still to be in excellent condition.

Section 7

STRIP CHART RECORDER TEST RESULTS

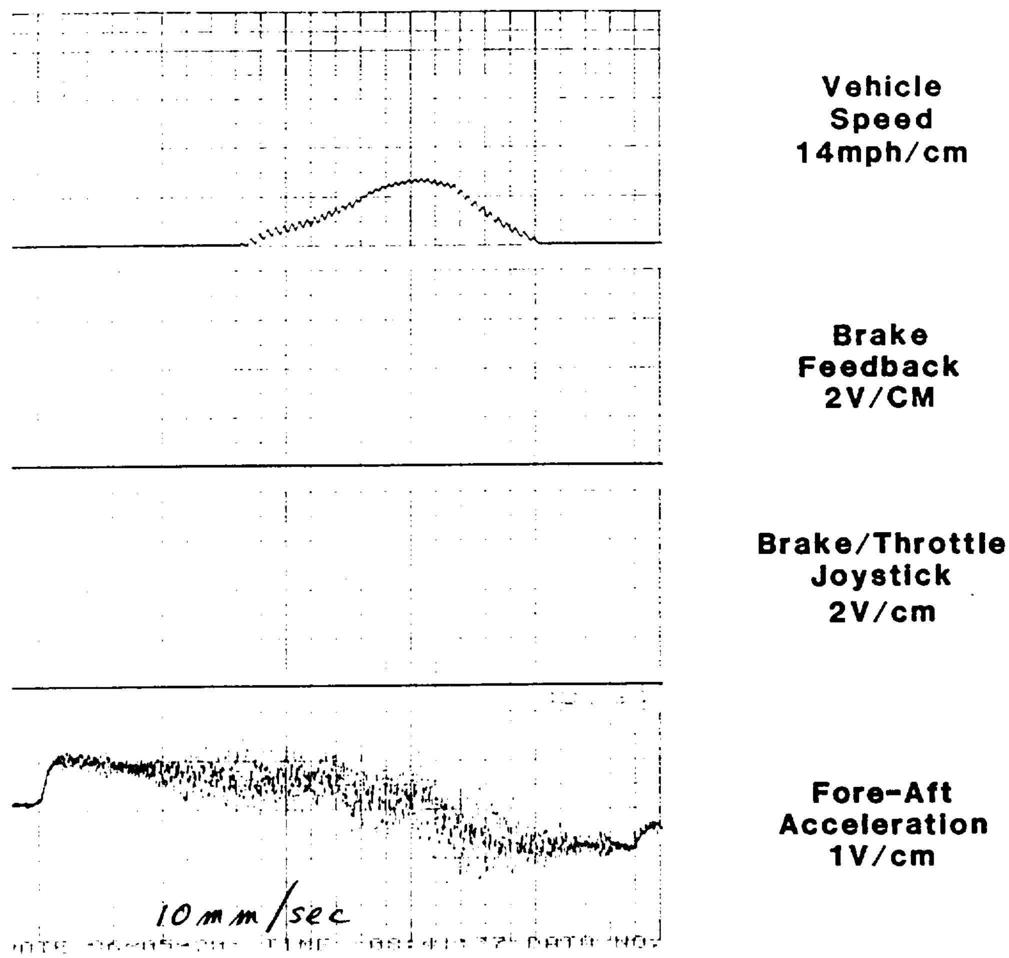


FIGURE C-1. TEST 1.1.1

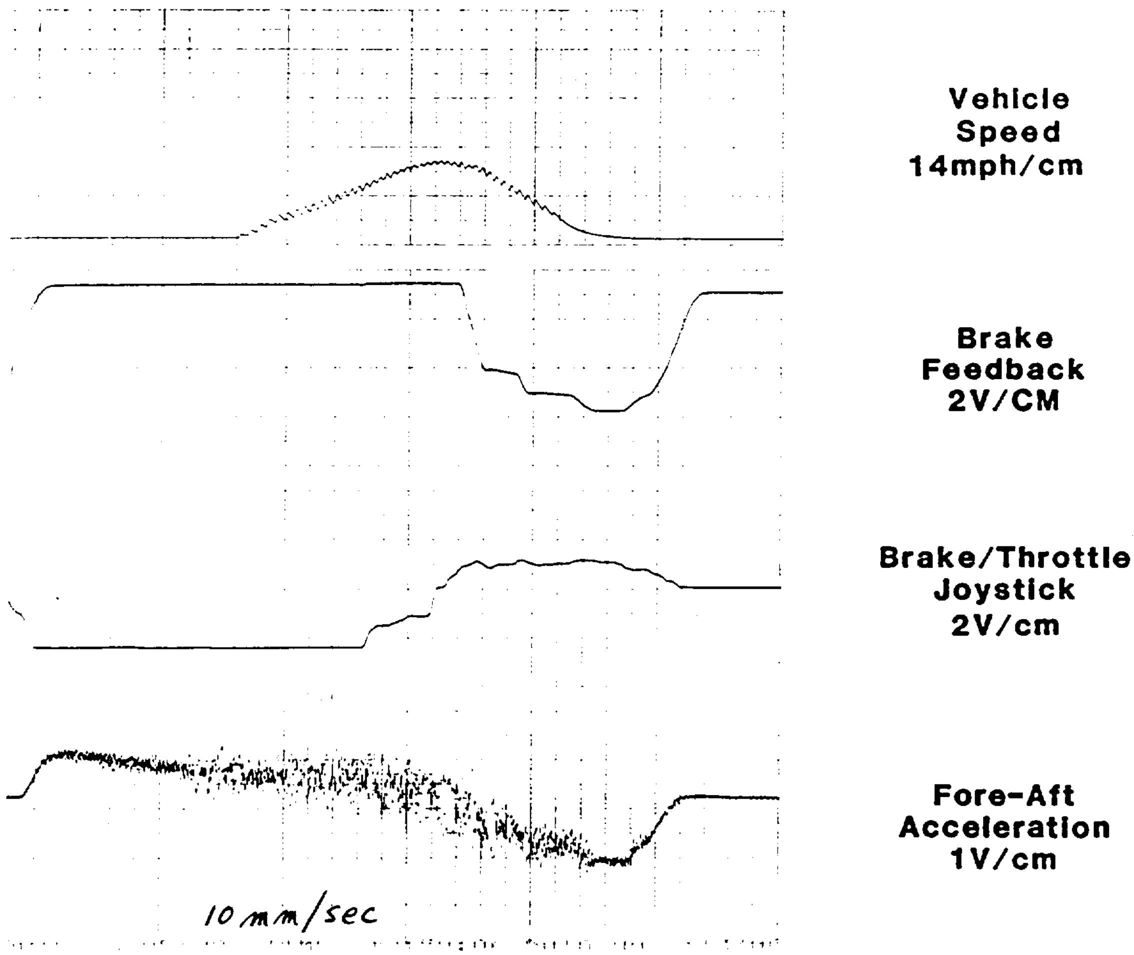


FIGURE C-2. TEST 1.1.1.J

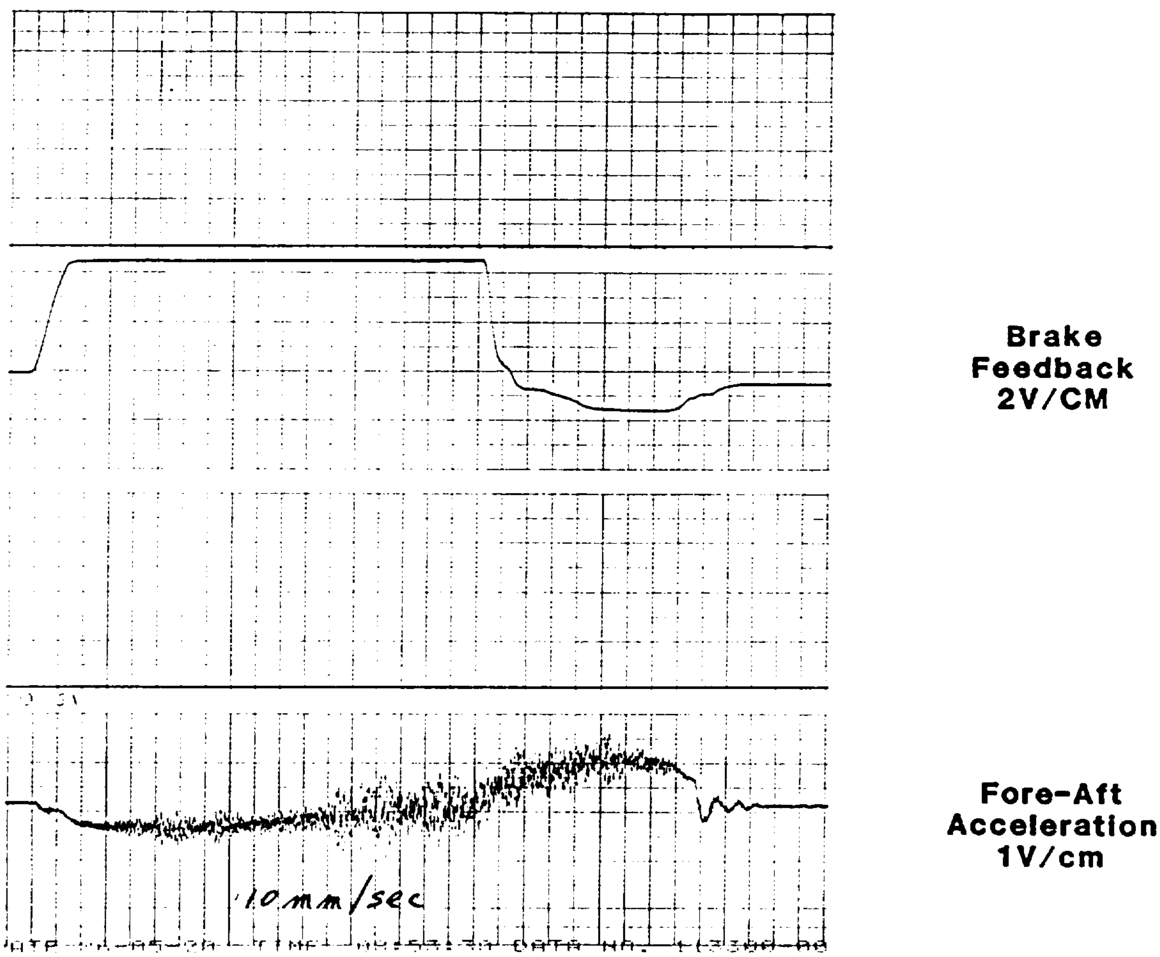


FIGURE C-3. TEST 1.1.2

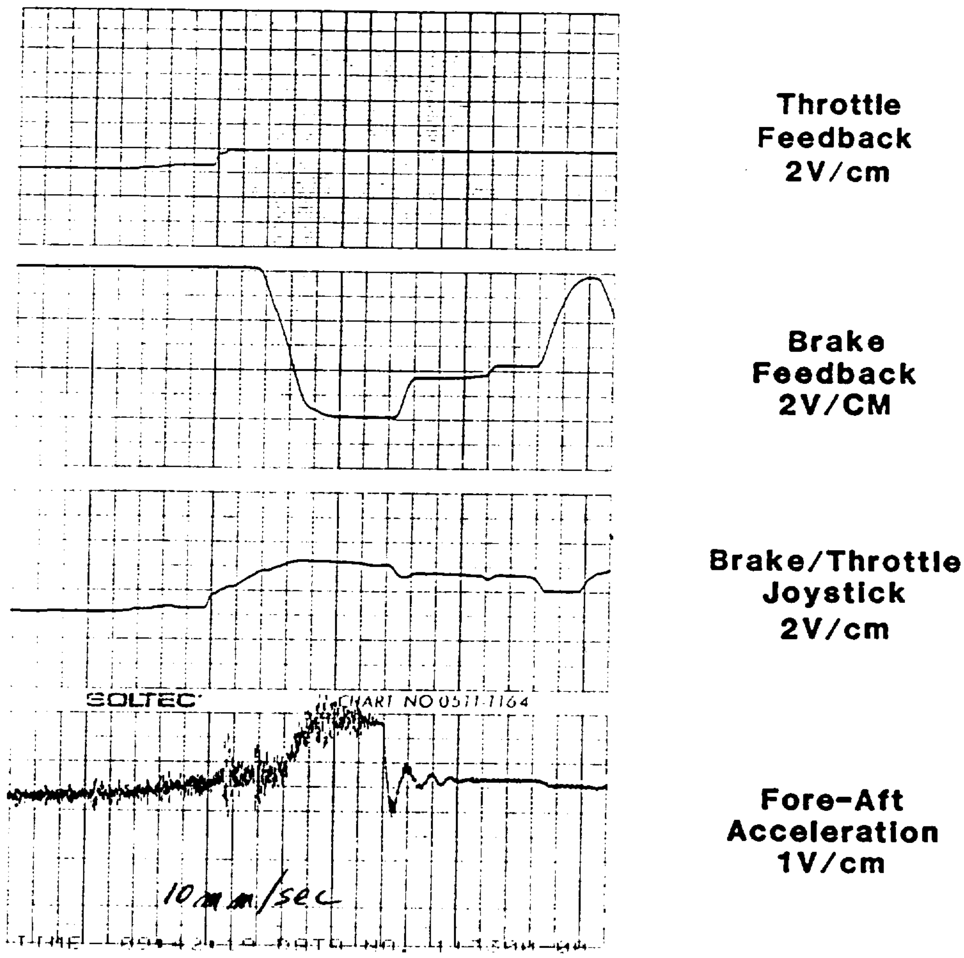


FIGURE C-4. TEST 1.1.2(J)

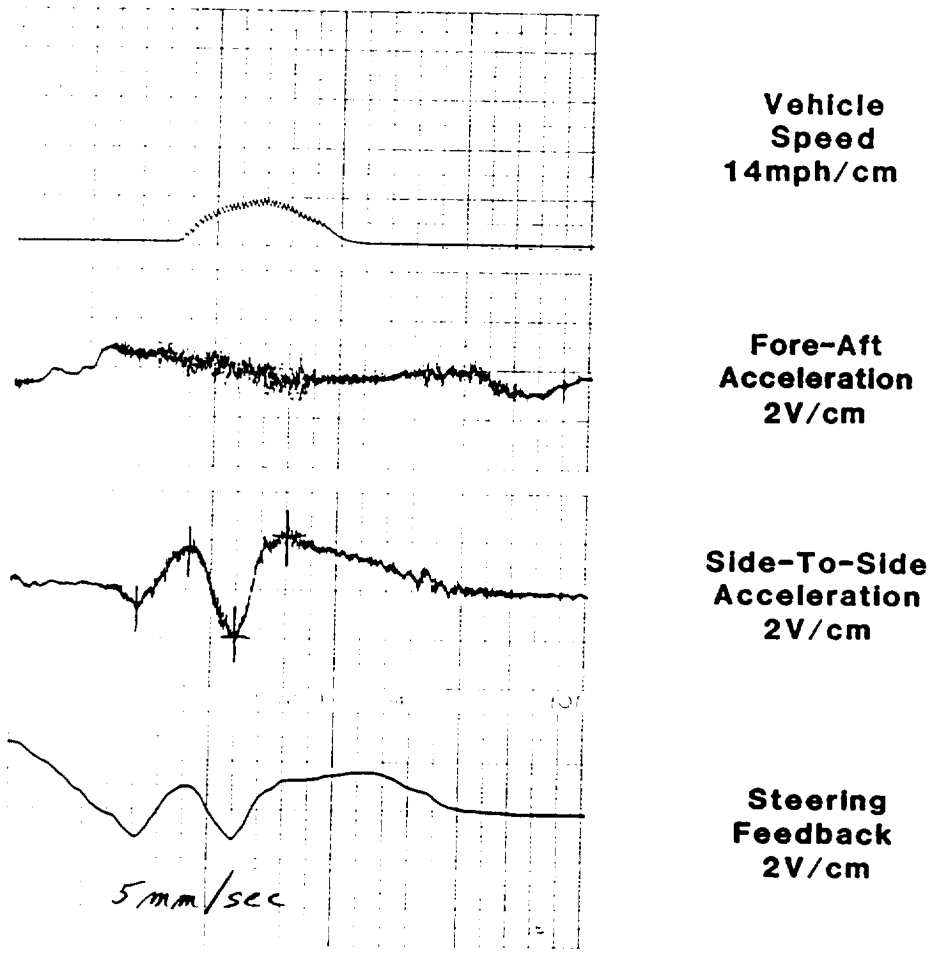


FIGURE C-5. TEST 1.1.6

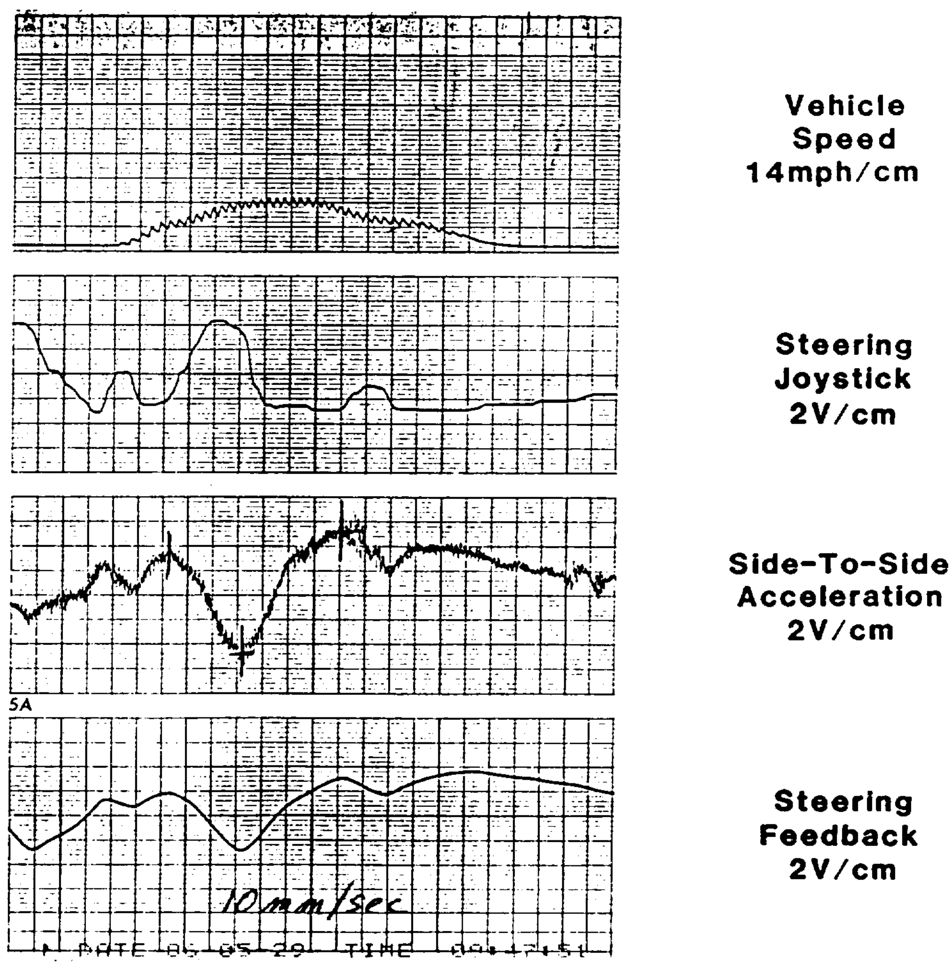


FIGURE C-6. TEST 1.1.6(J)

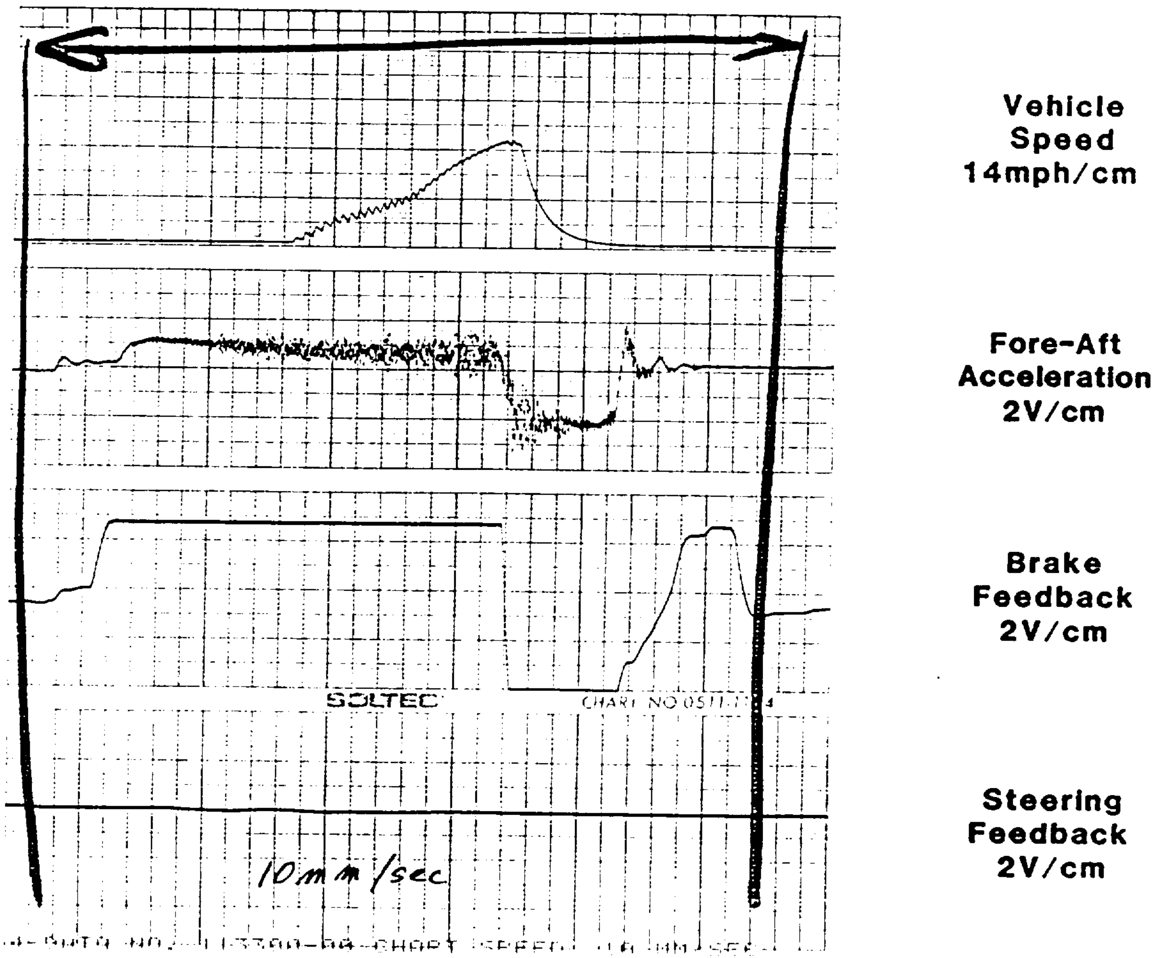


FIGURE C-7. TEST 1.1.7

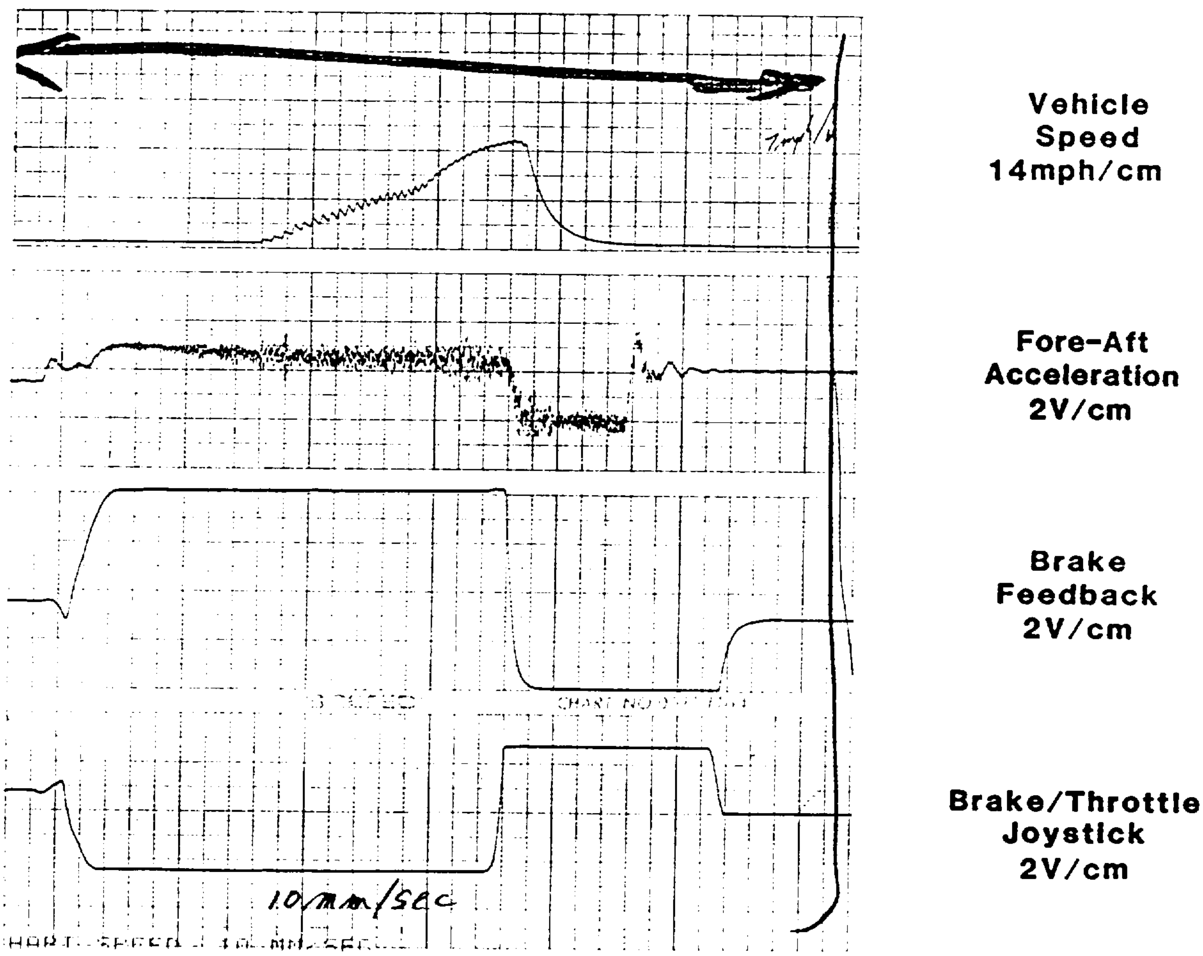


FIGURE C-8. TEST 1.1.7(J)

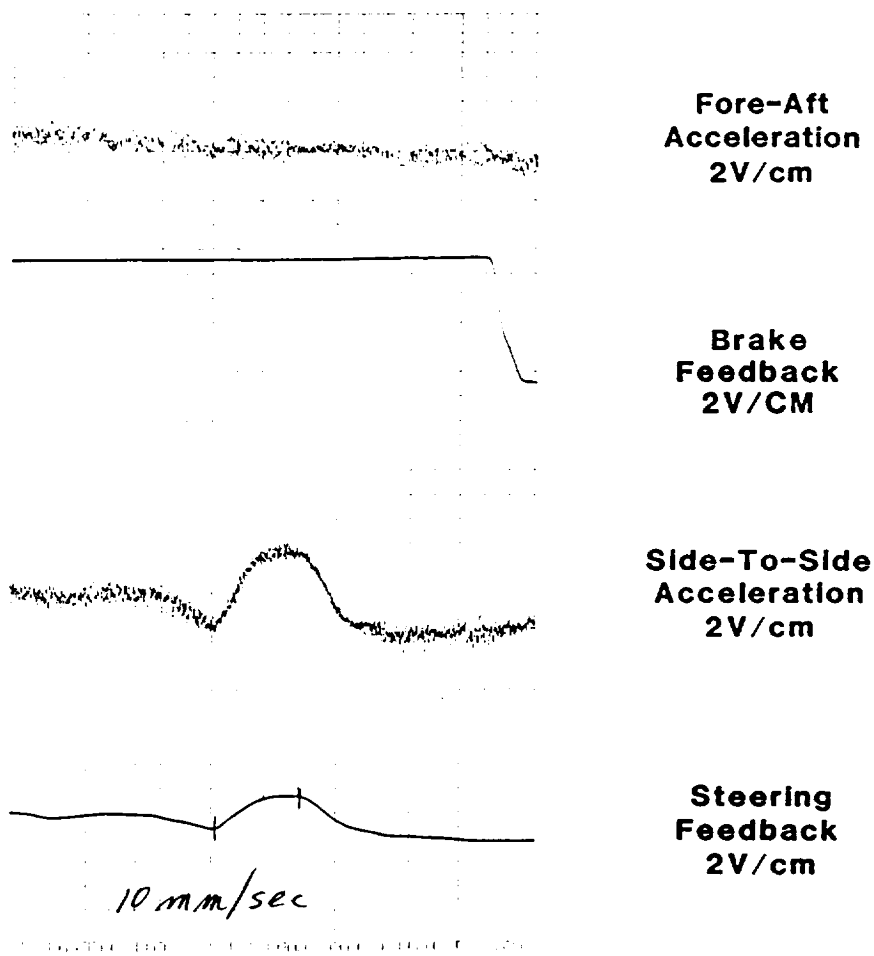


FIGURE C-9. TEST 1.1.8

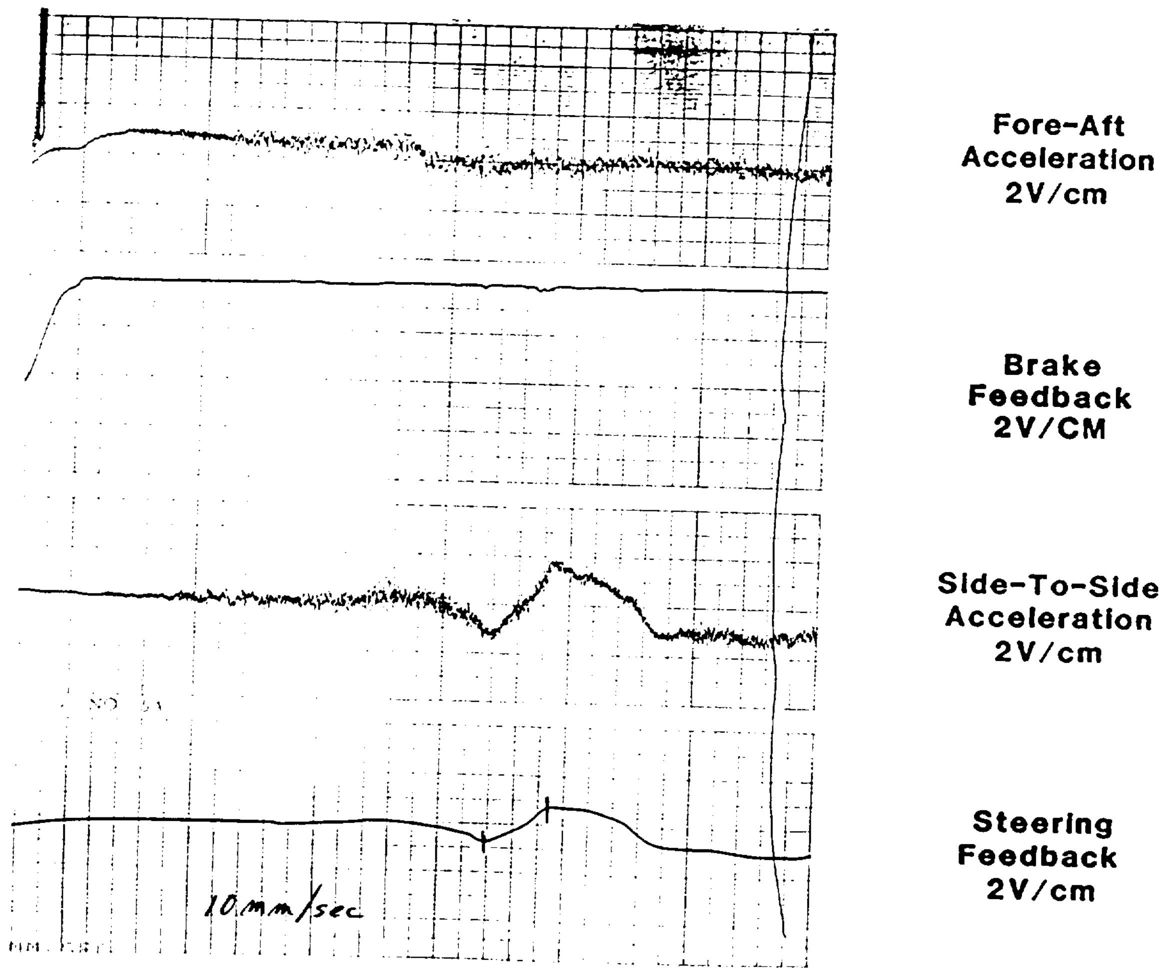


FIGURE C-10. TEST 1.1.8(J)

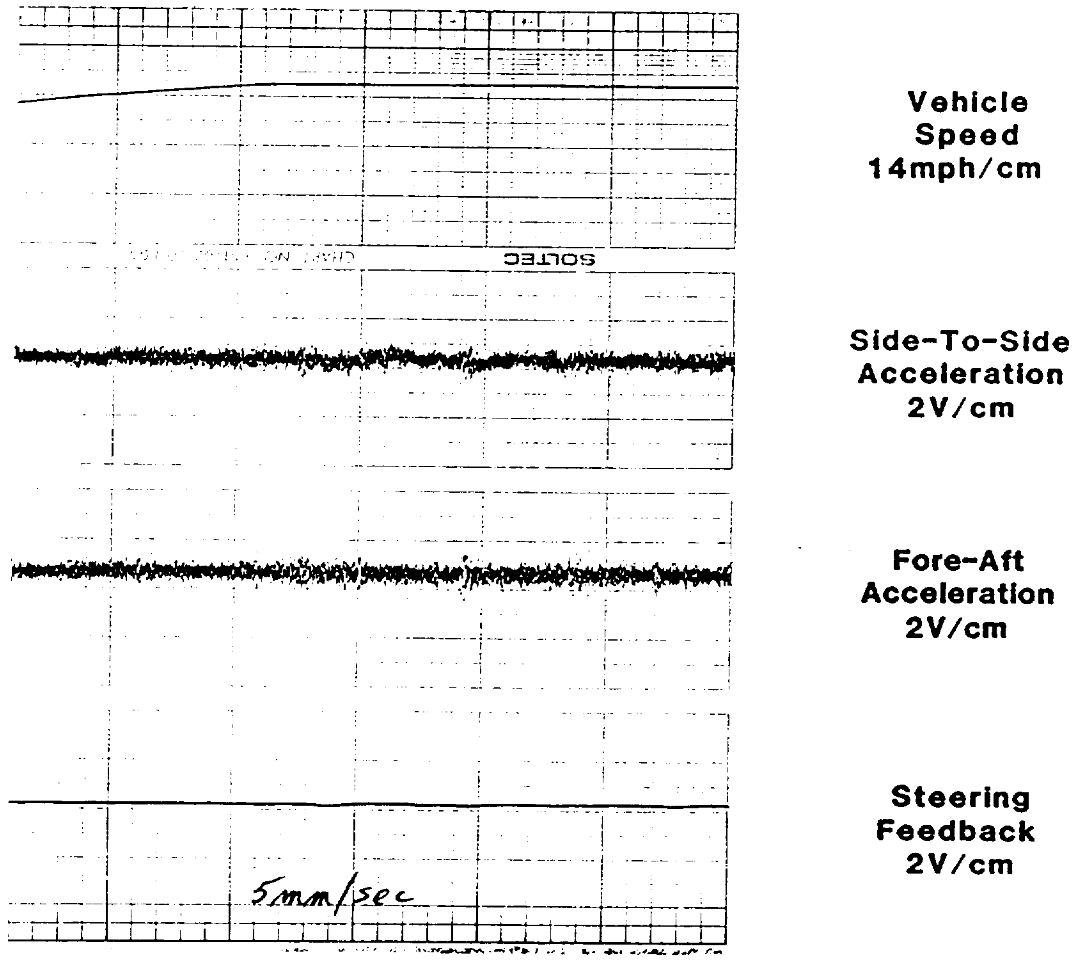


FIGURE C-11. TEST 1.2.1(J)

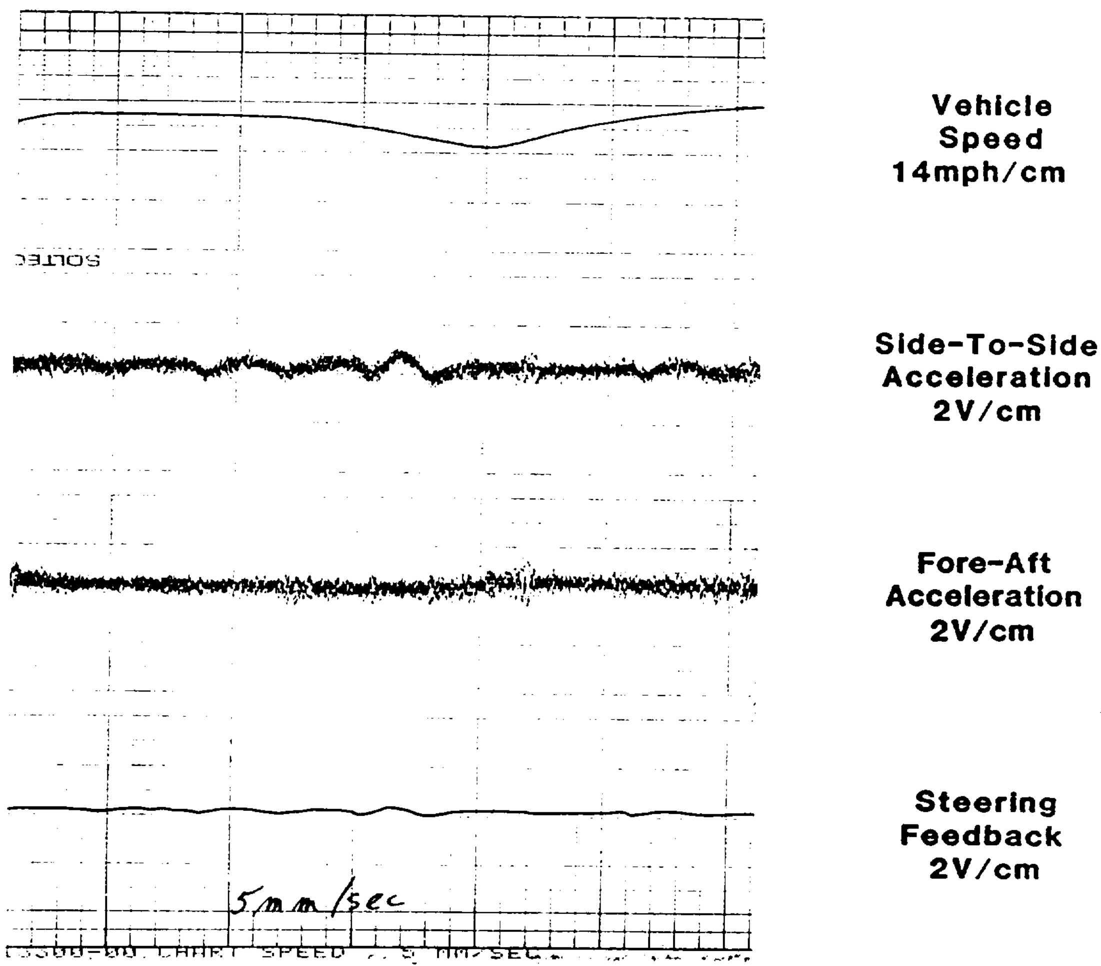


FIGURE C-12. TEST 1.2.1(J)

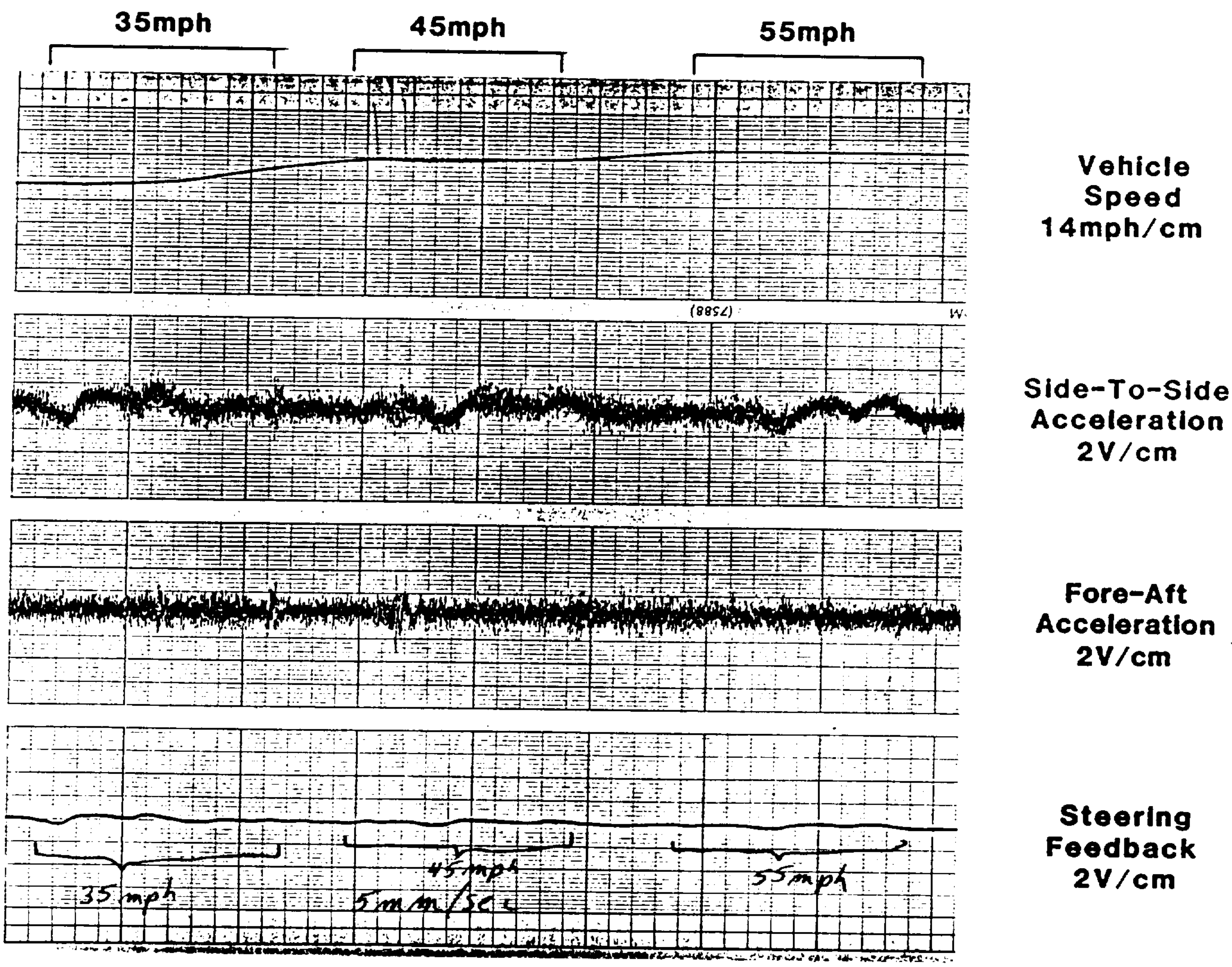


FIGURE C-13. TEST 1.2.2

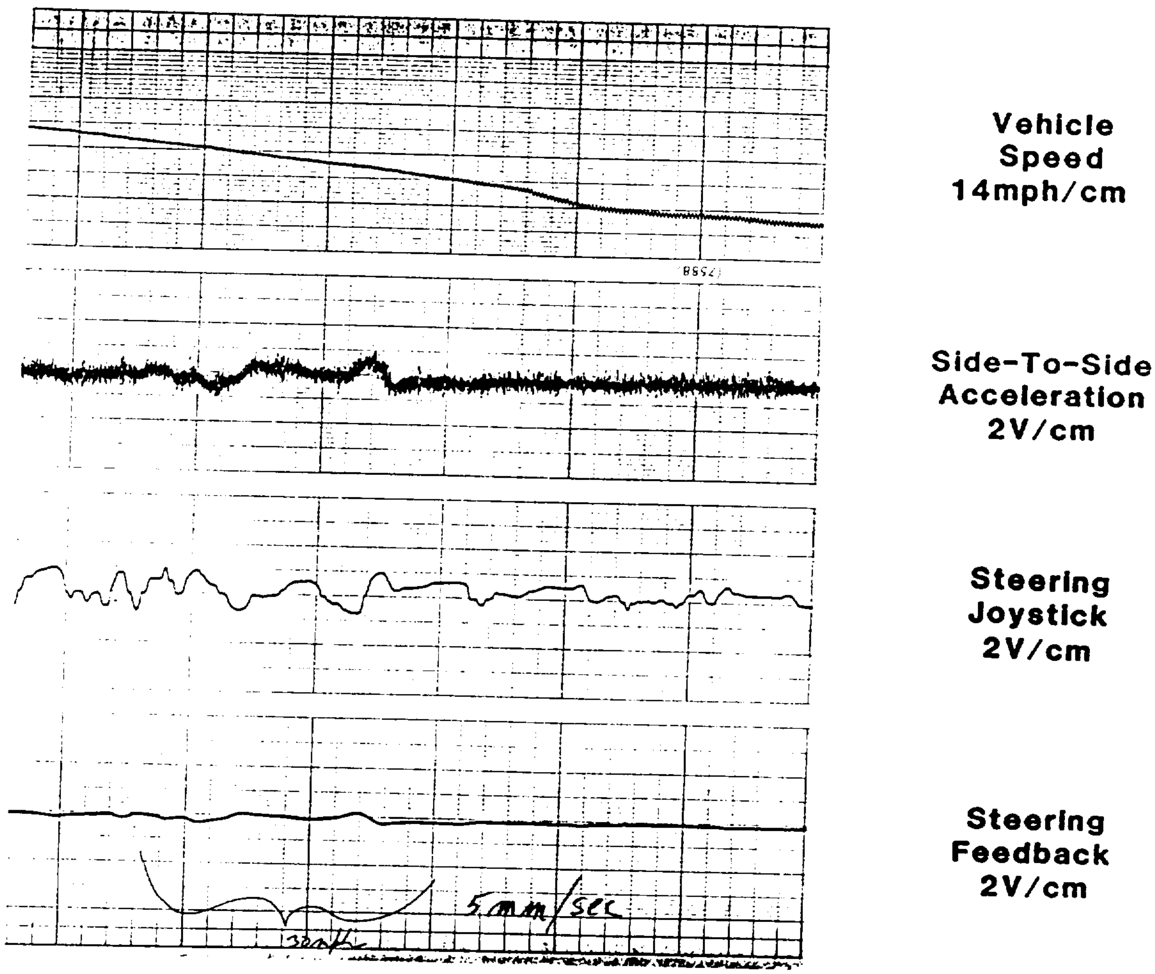


FIGURE C-14. TEST 1.2.2(J)

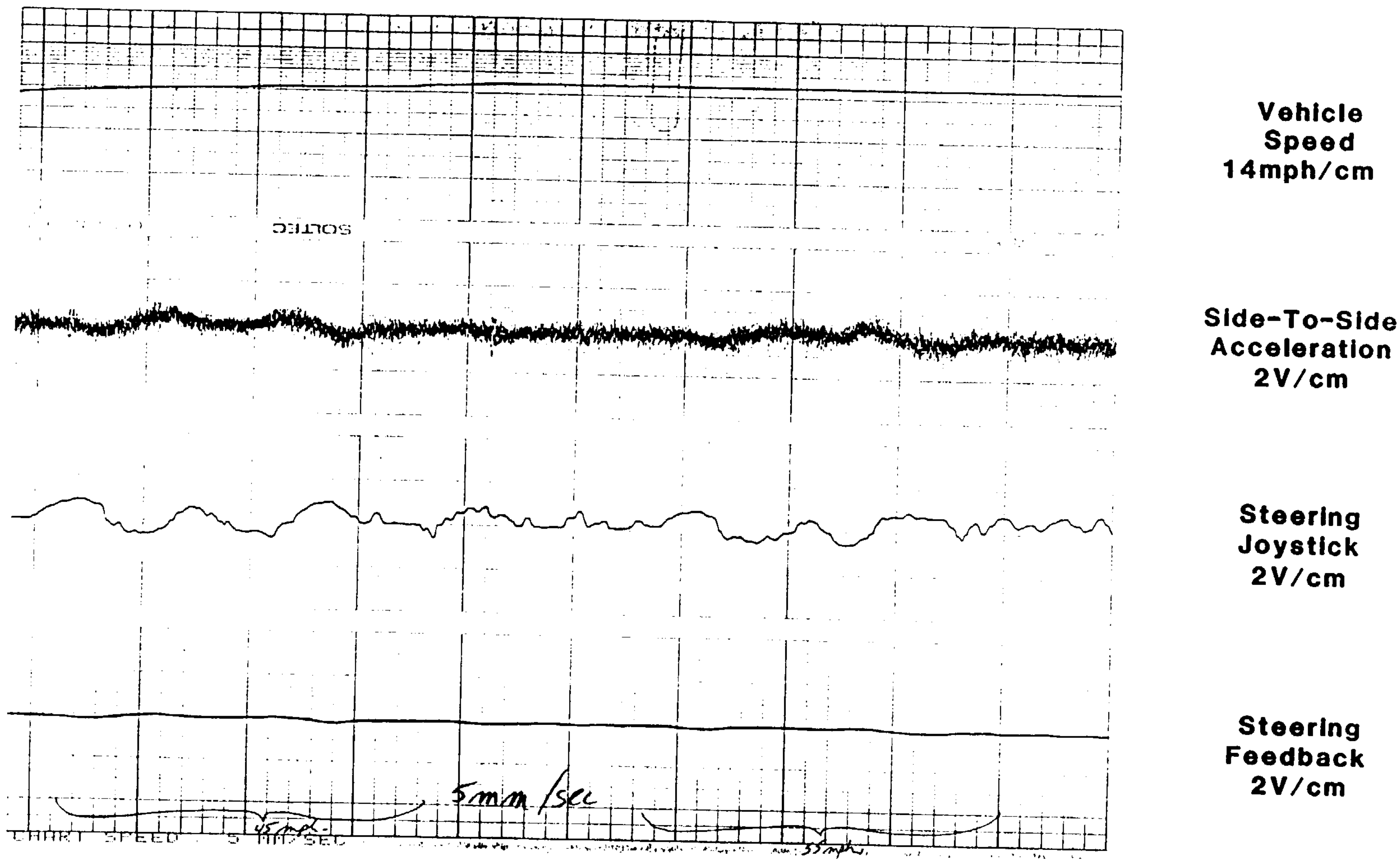


FIGURE C-15. TEST 1.2.2(J)

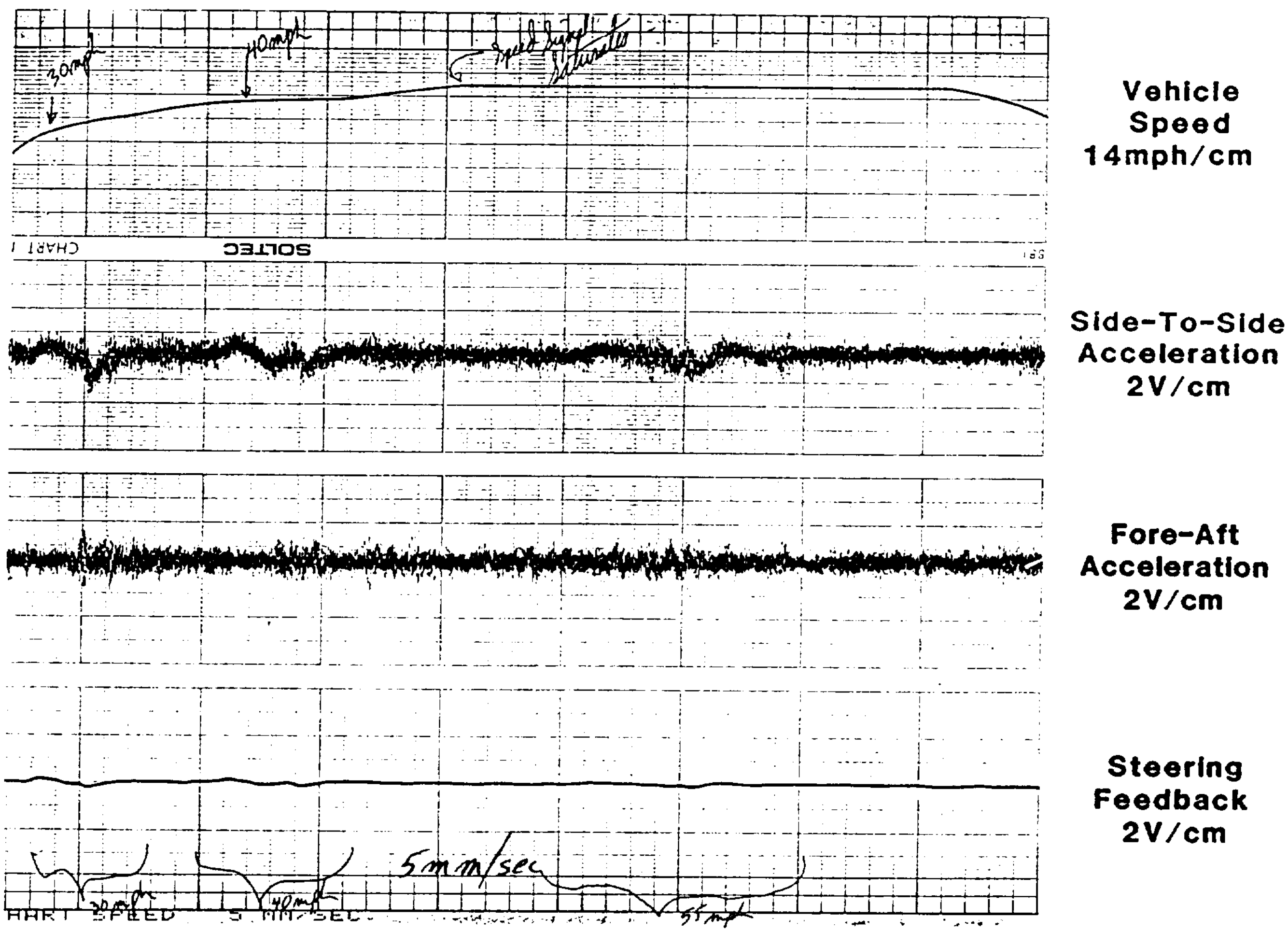


FIGURE C-16. TEST 1.2.3

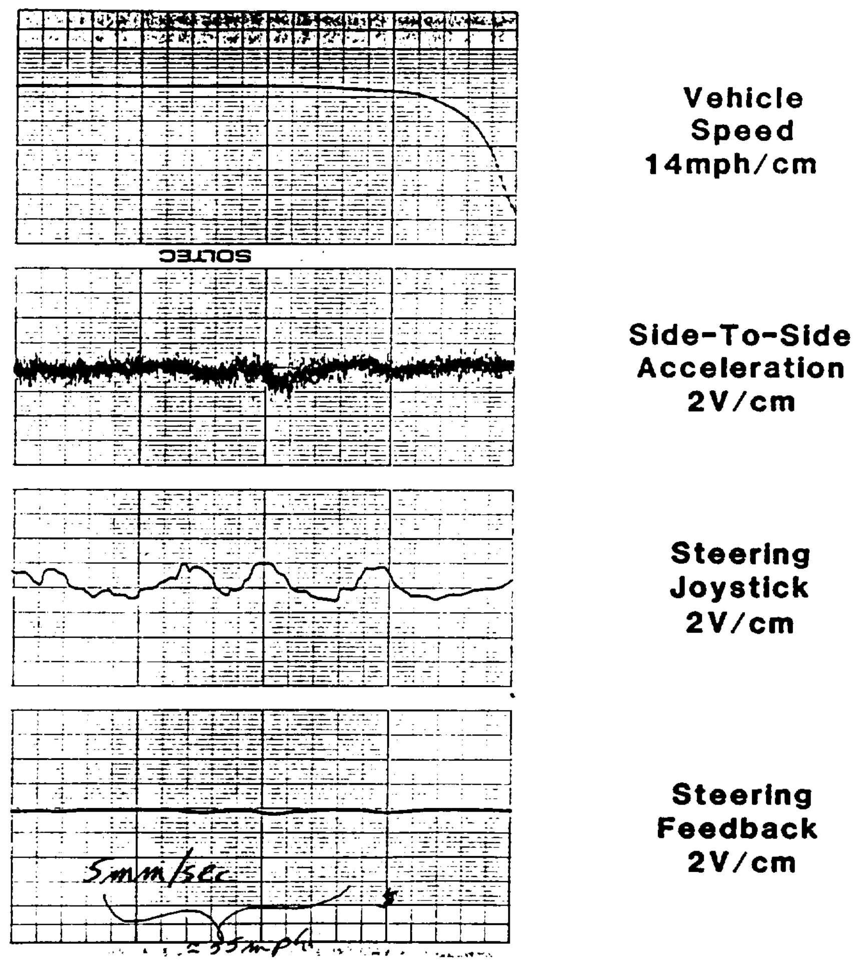


FIGURE C-17. TEST 1.2.3(J)

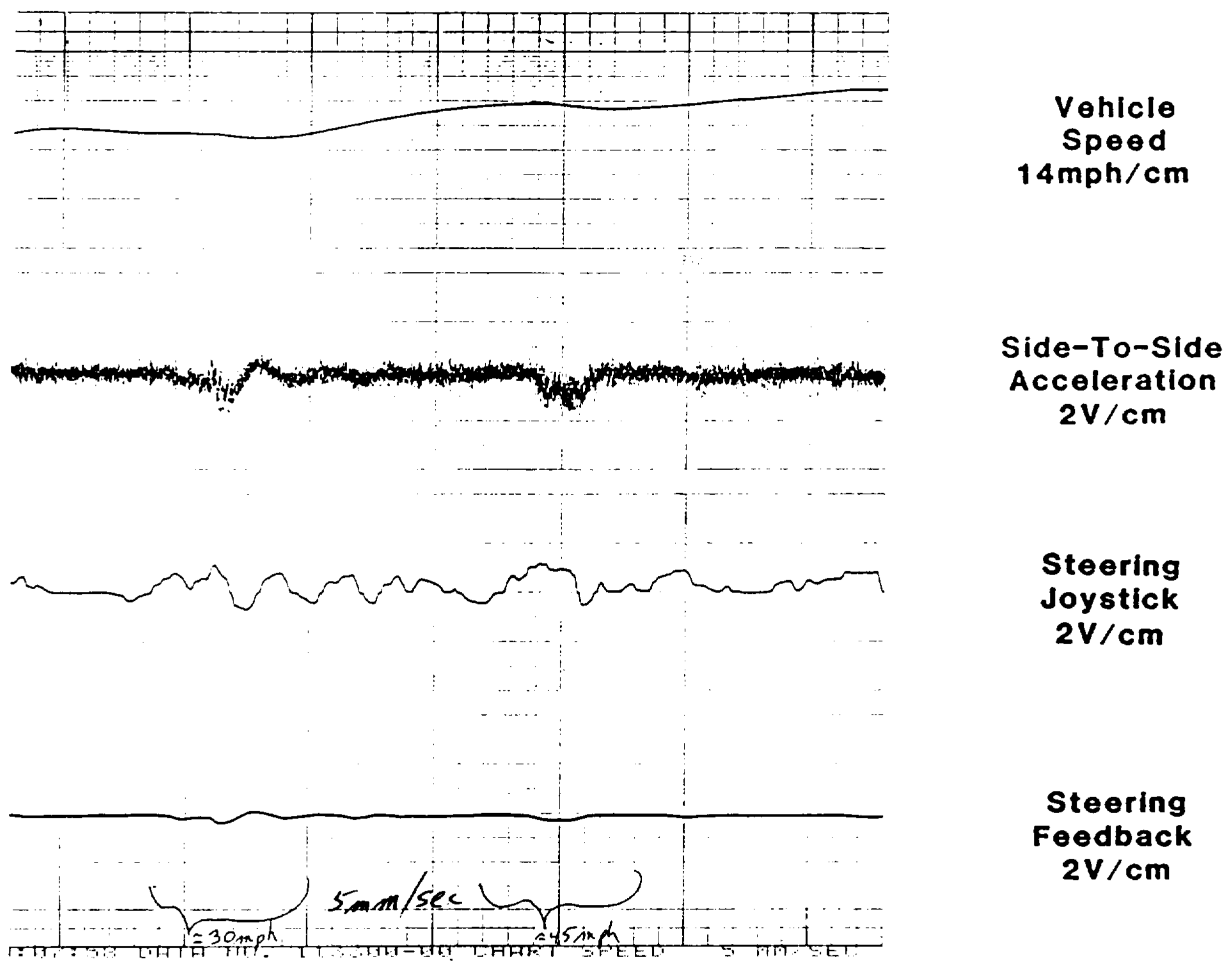


FIGURE C-18. TEST 1.2.3(J)

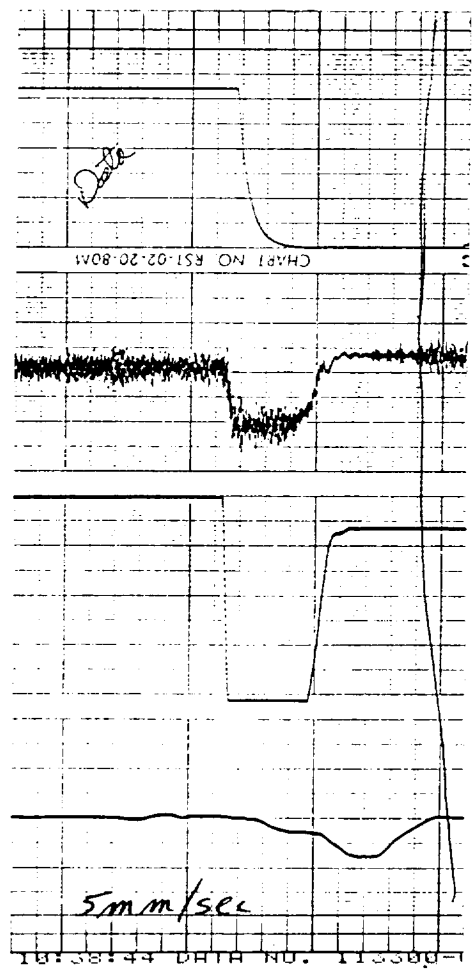
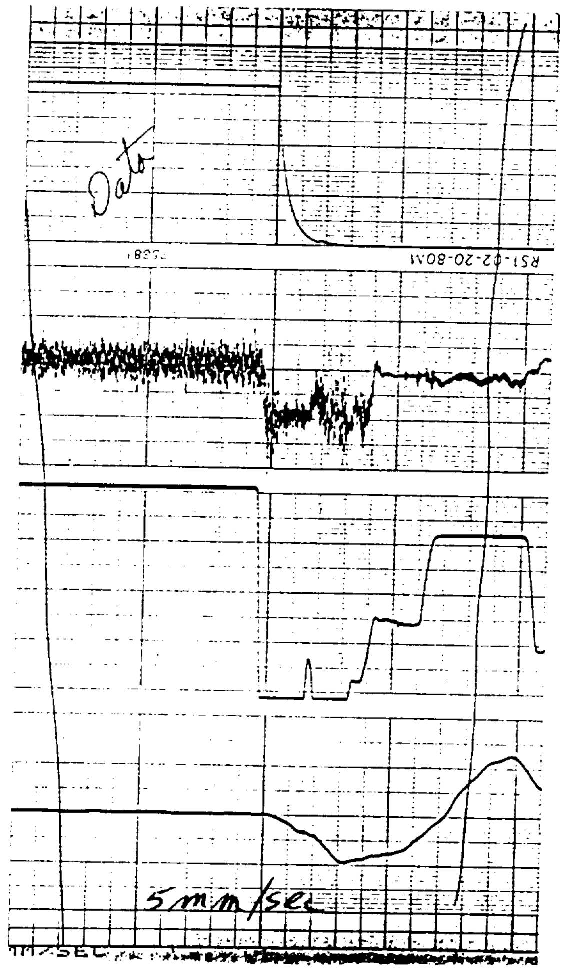


FIGURE C-19. TEST 1.2.4



Vehicle Speed 14mph/cm

Fore-Aft Acceleration 2V/cm

Brake Feedback 2V/cm

Steering Feedback 2V/cm

FIGURE C-20. TEST 1.2.4

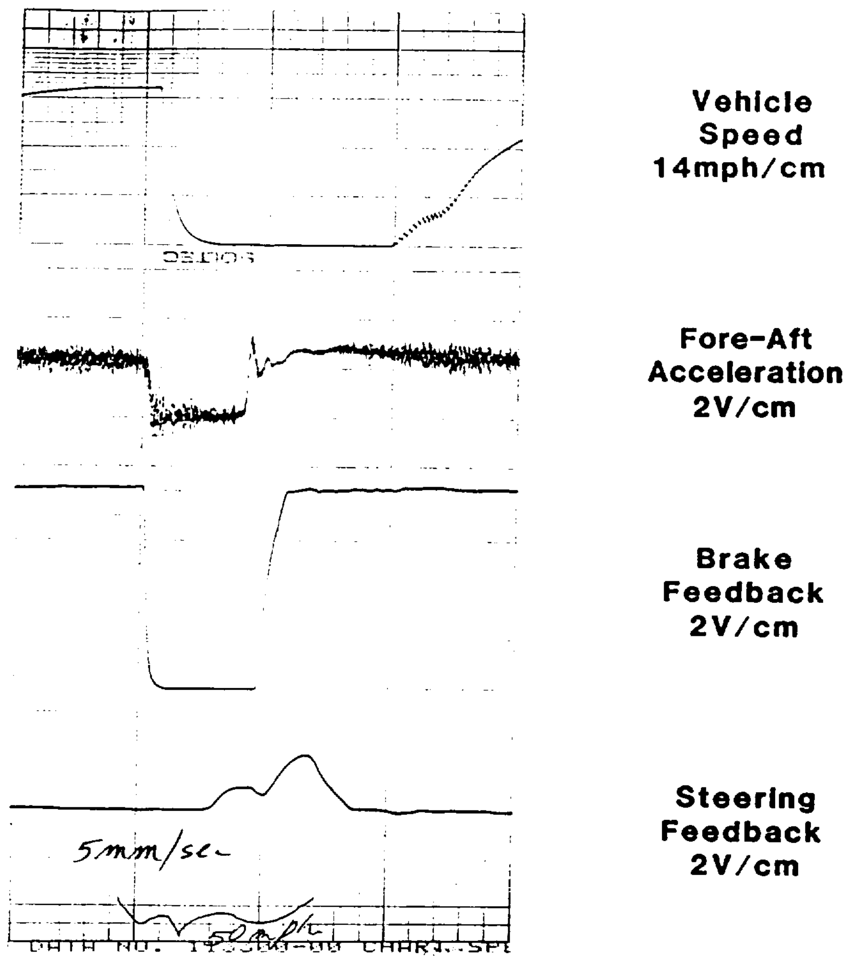


FIGURE C-21. TEST 1.2.4(J)

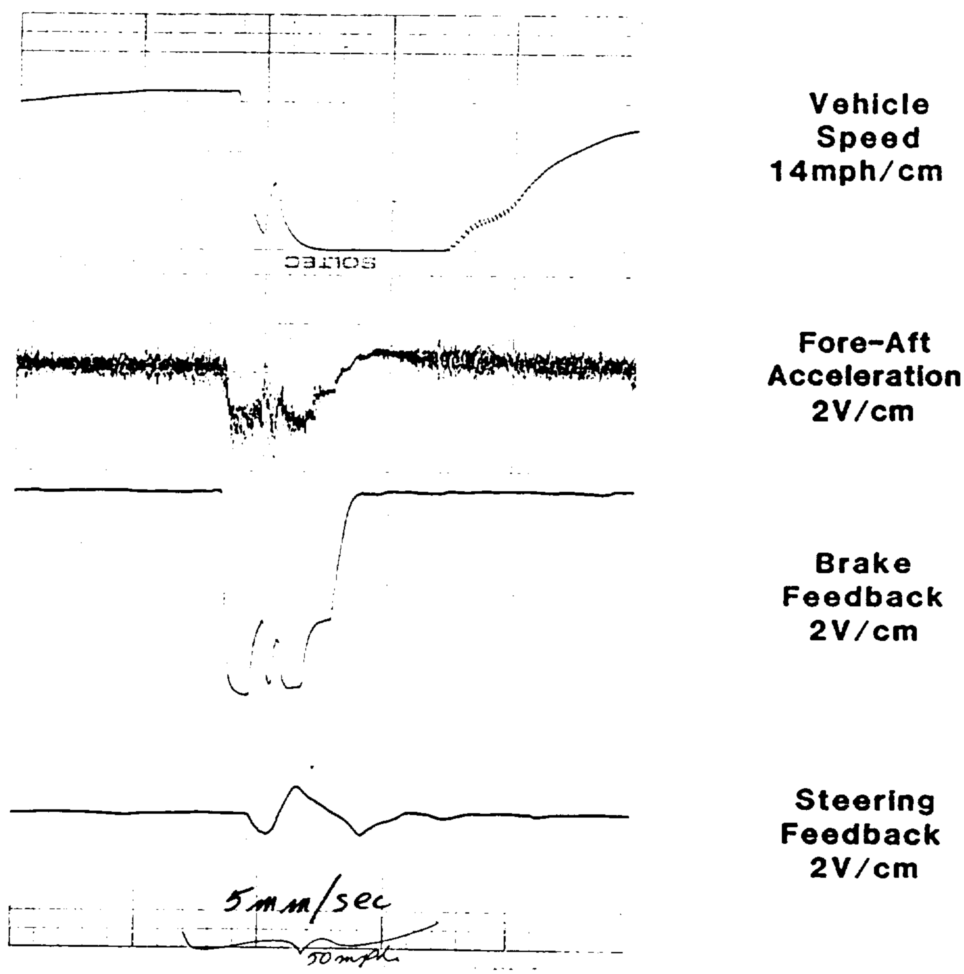
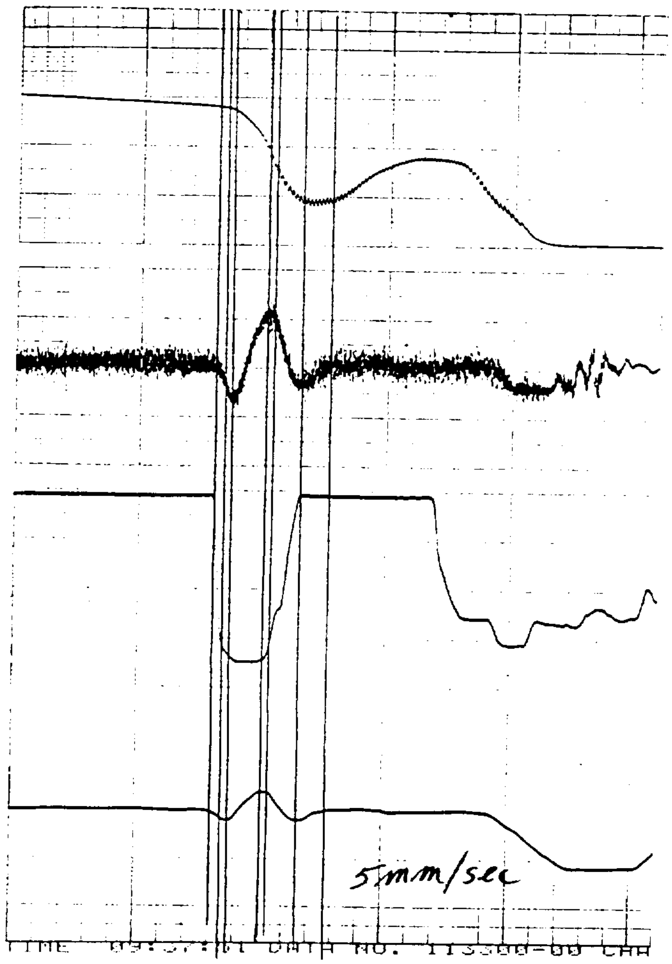


FIGURE C-22. TEST 1.2.4(J)



Vehicle Speed 14mph/cm

Side-To-Side Acceleration 2V/cm

Brake Feedback 2V/cm

Steering Feedback 2V/cm

FIGURE C-23. TEST 1.2.5

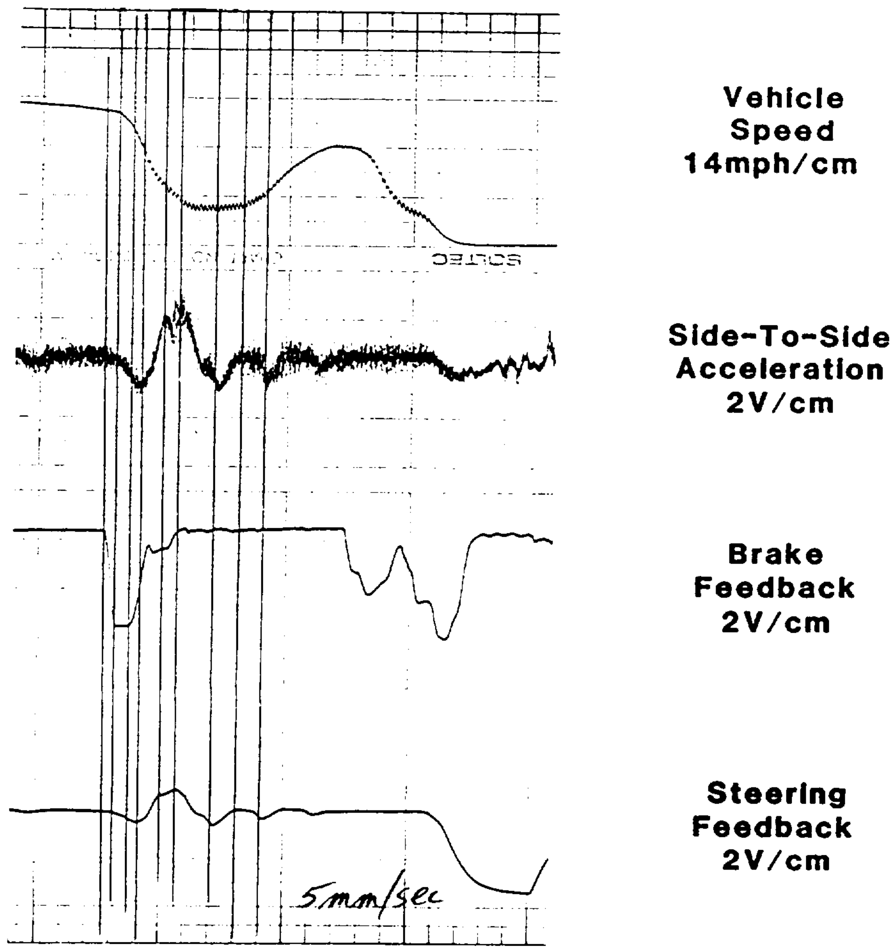


FIGURE C-24. TEST 1.2.5(J)

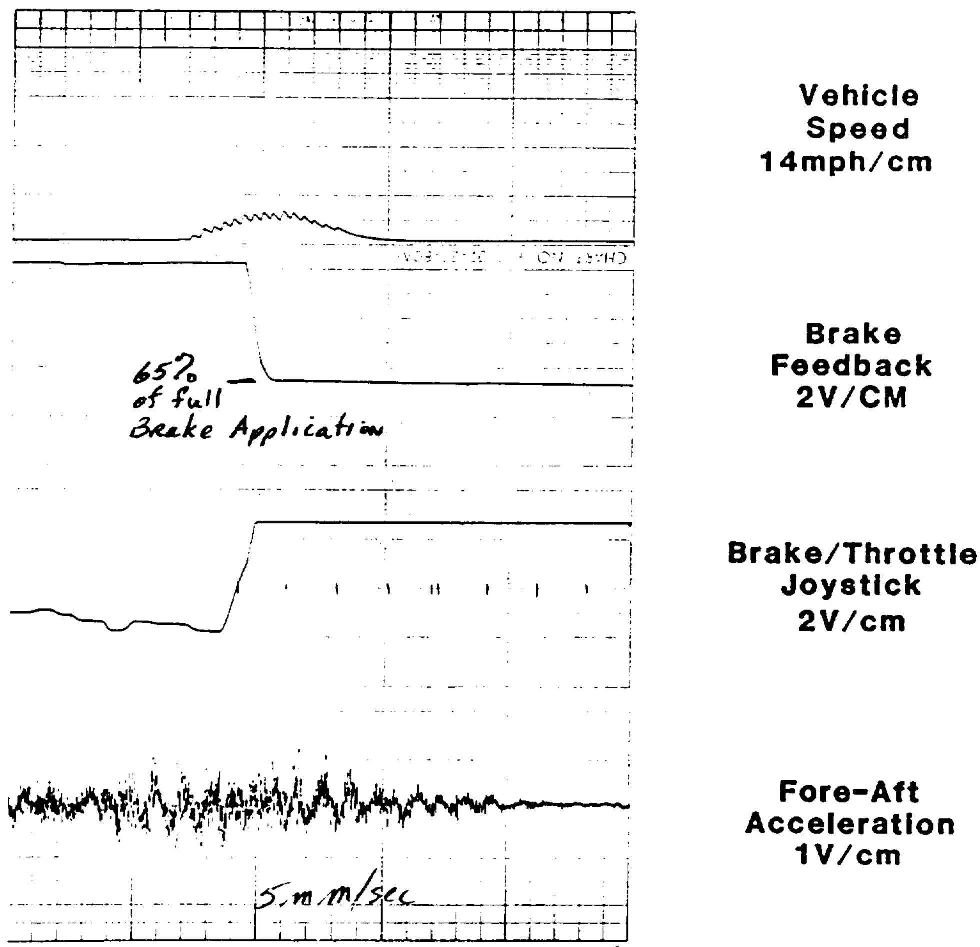


FIGURE C-25. TEST 2.1.1.1

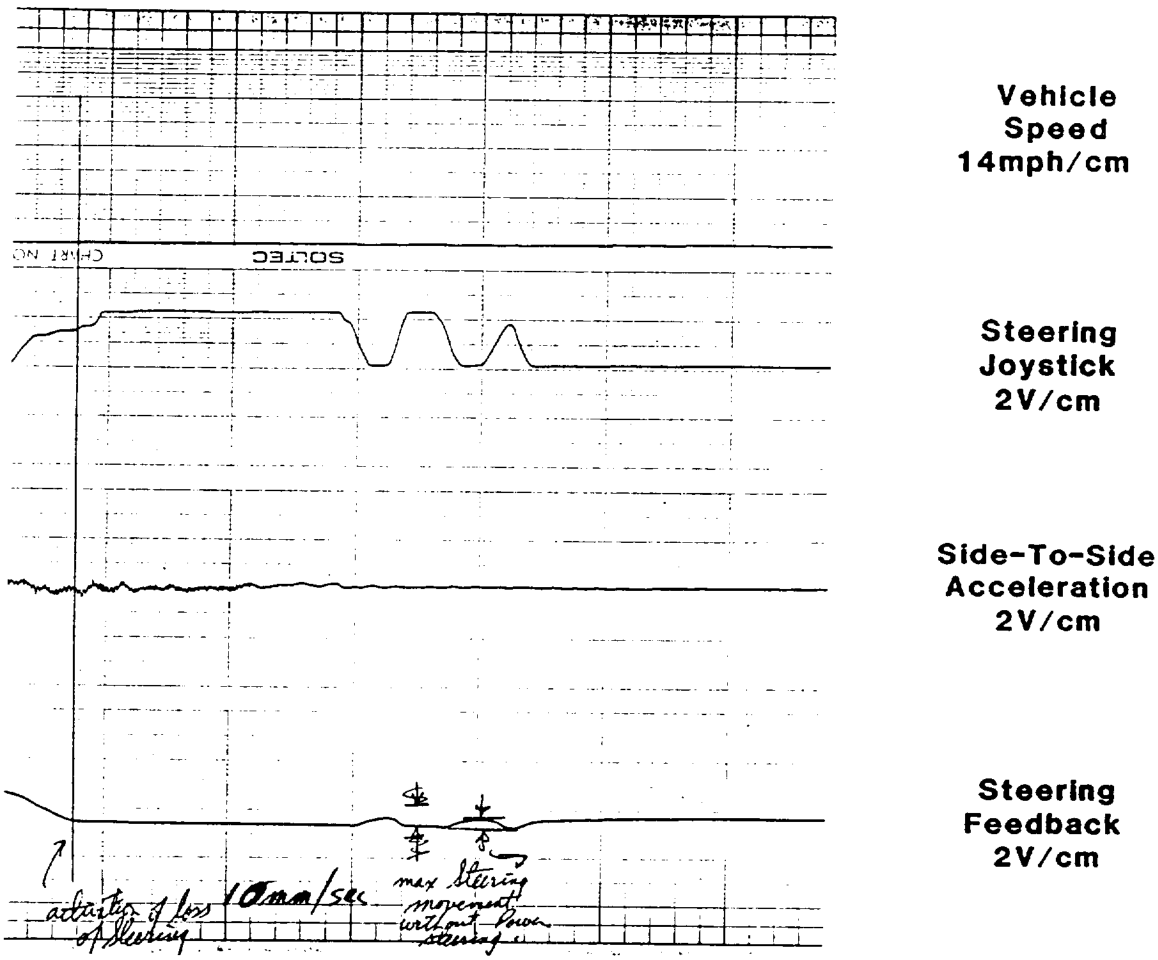


FIGURE C-26. TEST 2.1.2.1

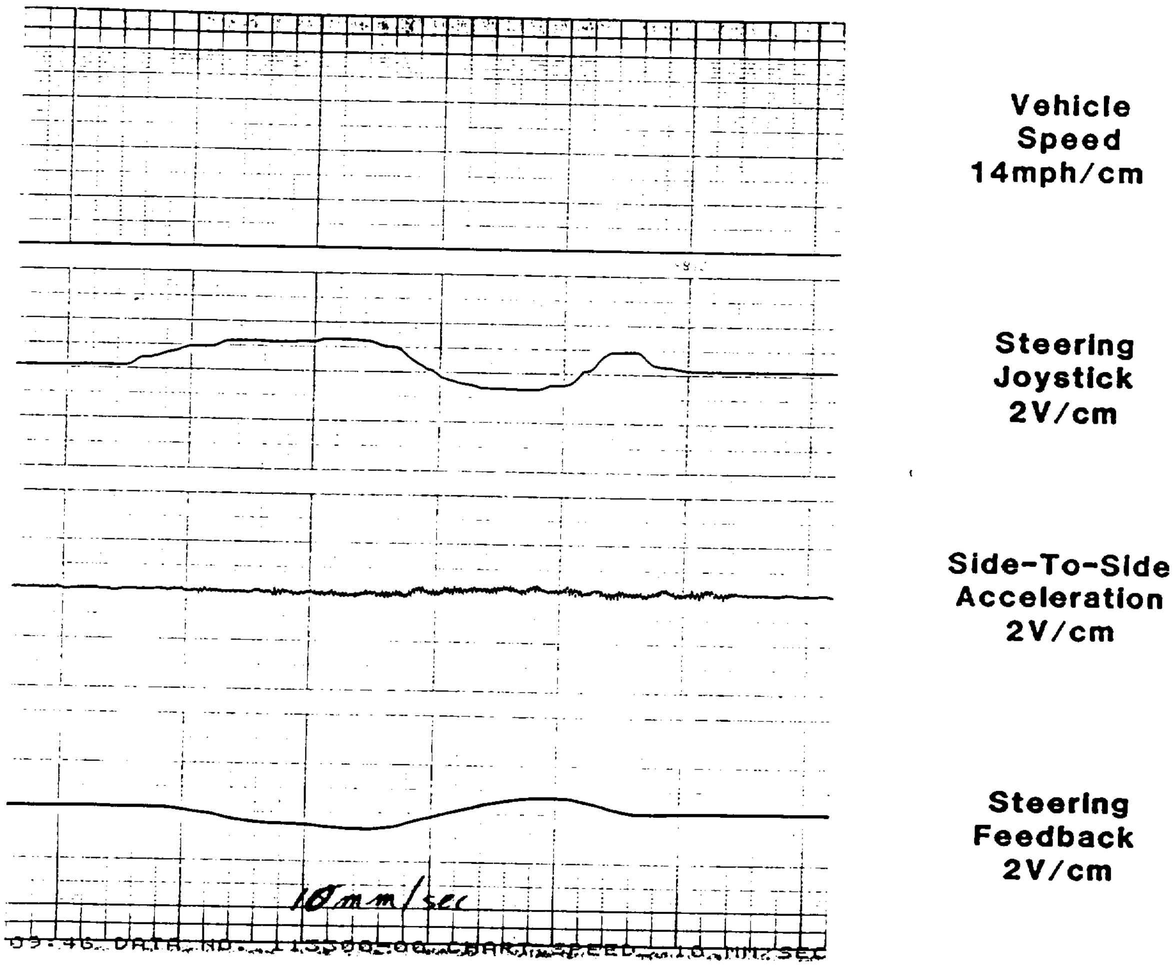


FIGURE C-27. TEST 2.1.3.1

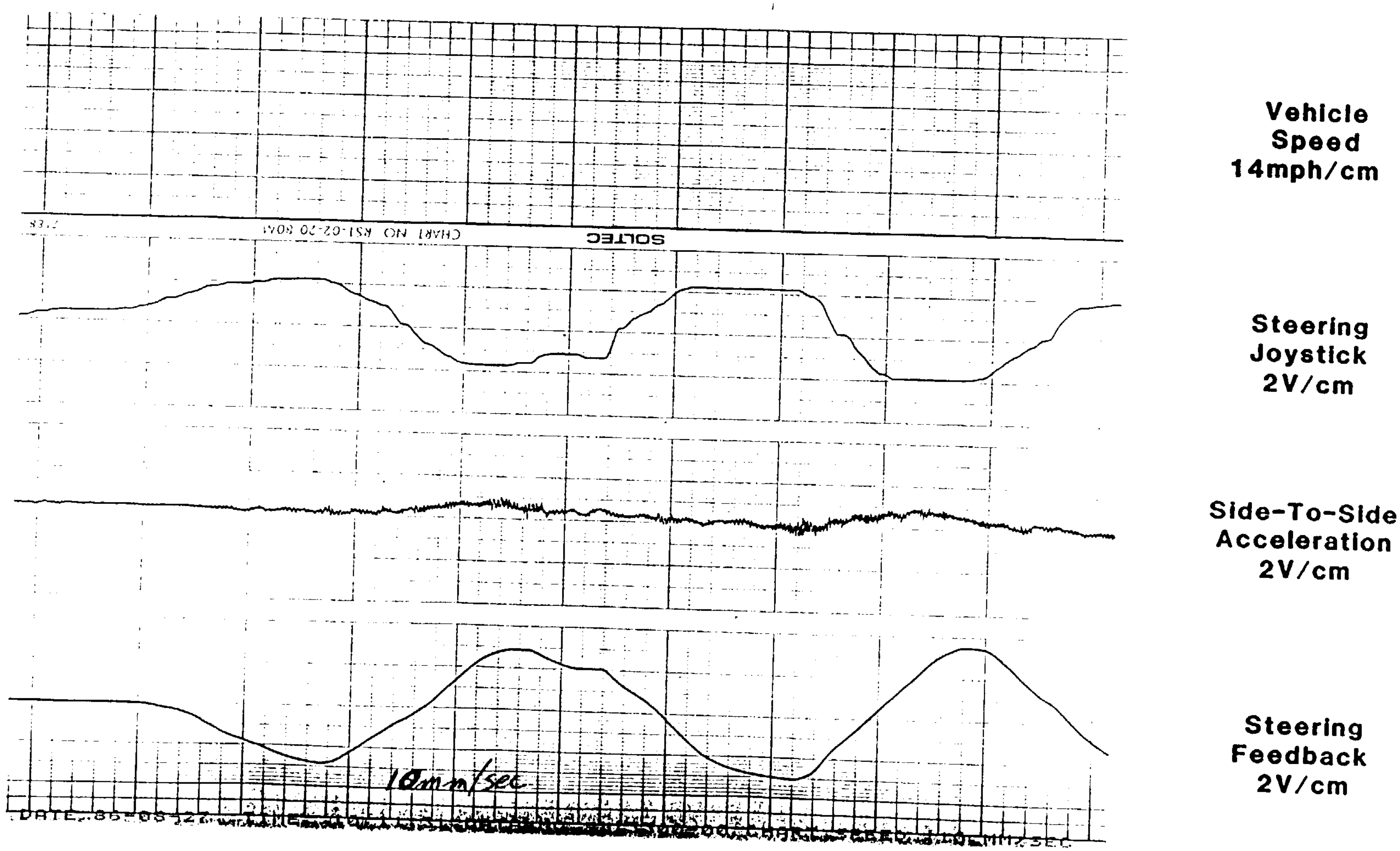


FIGURE C-28. TEST 2.1.3.2

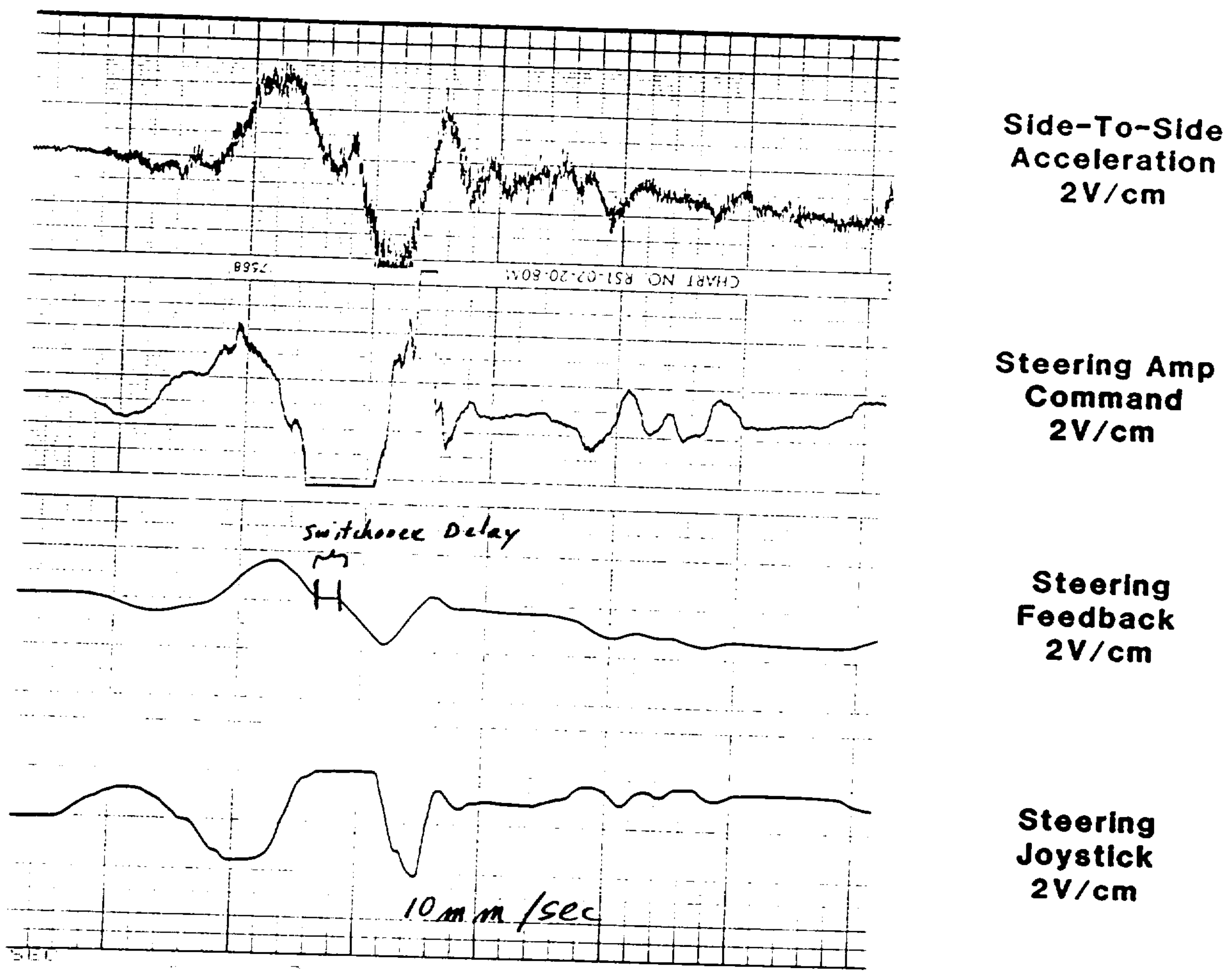


FIGURE C-29. TEST 3.1.1.1

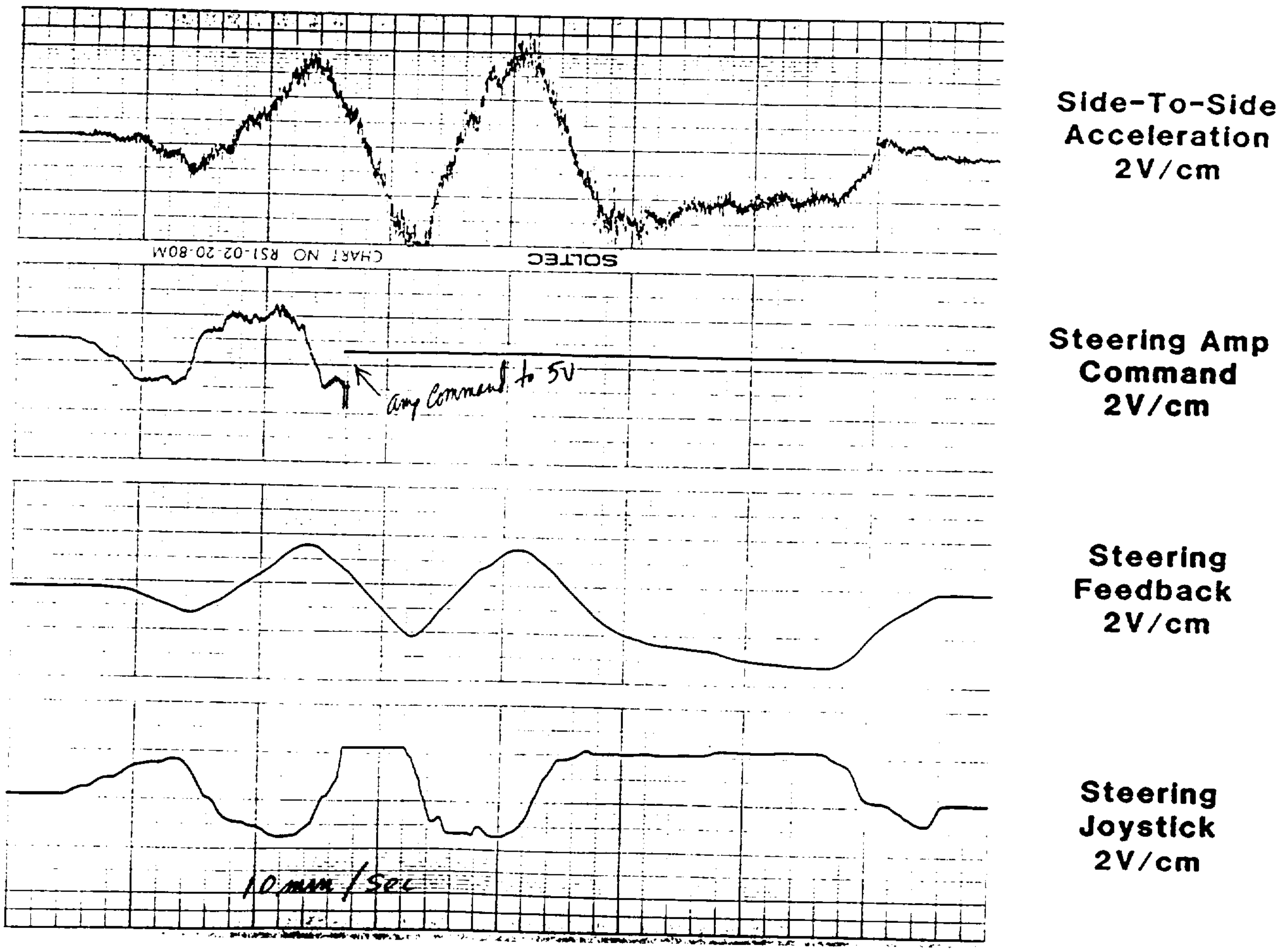


FIGURE C-30. TEST 3.1.1.2(A)

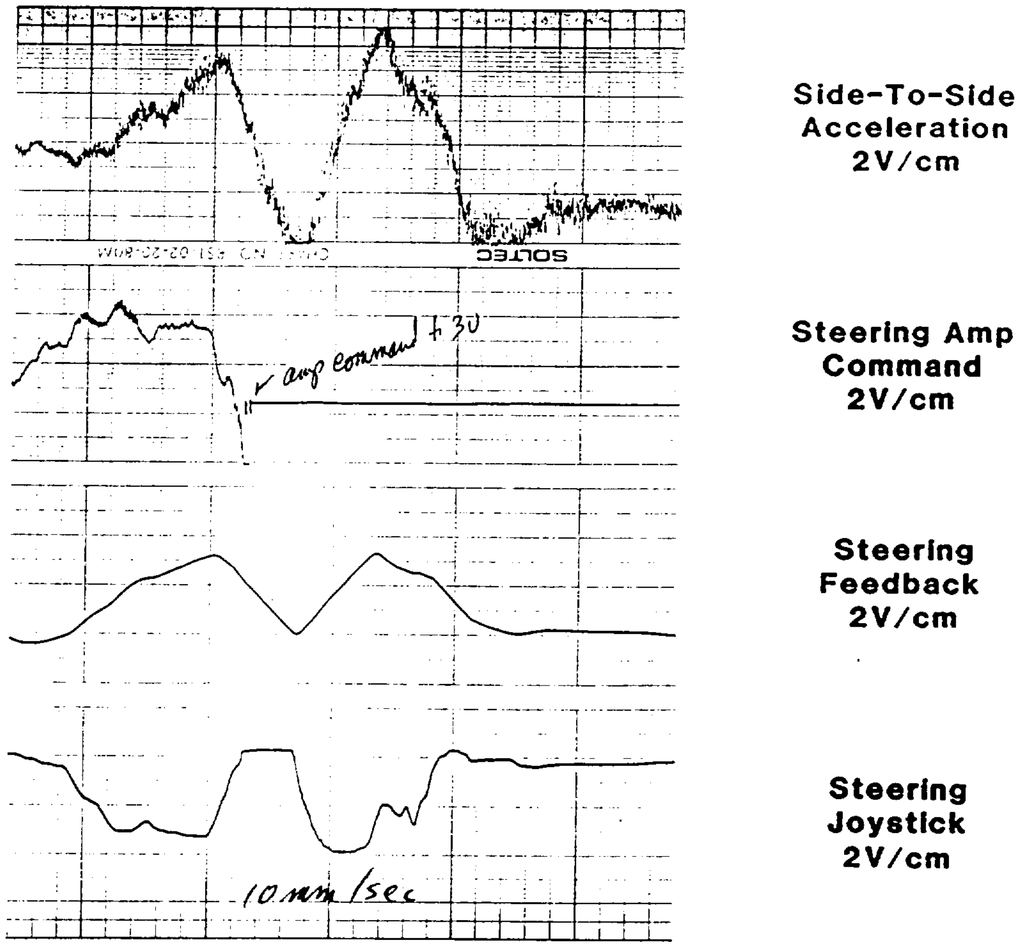


FIGURE C-31. TEST 3.1.1.2(B)

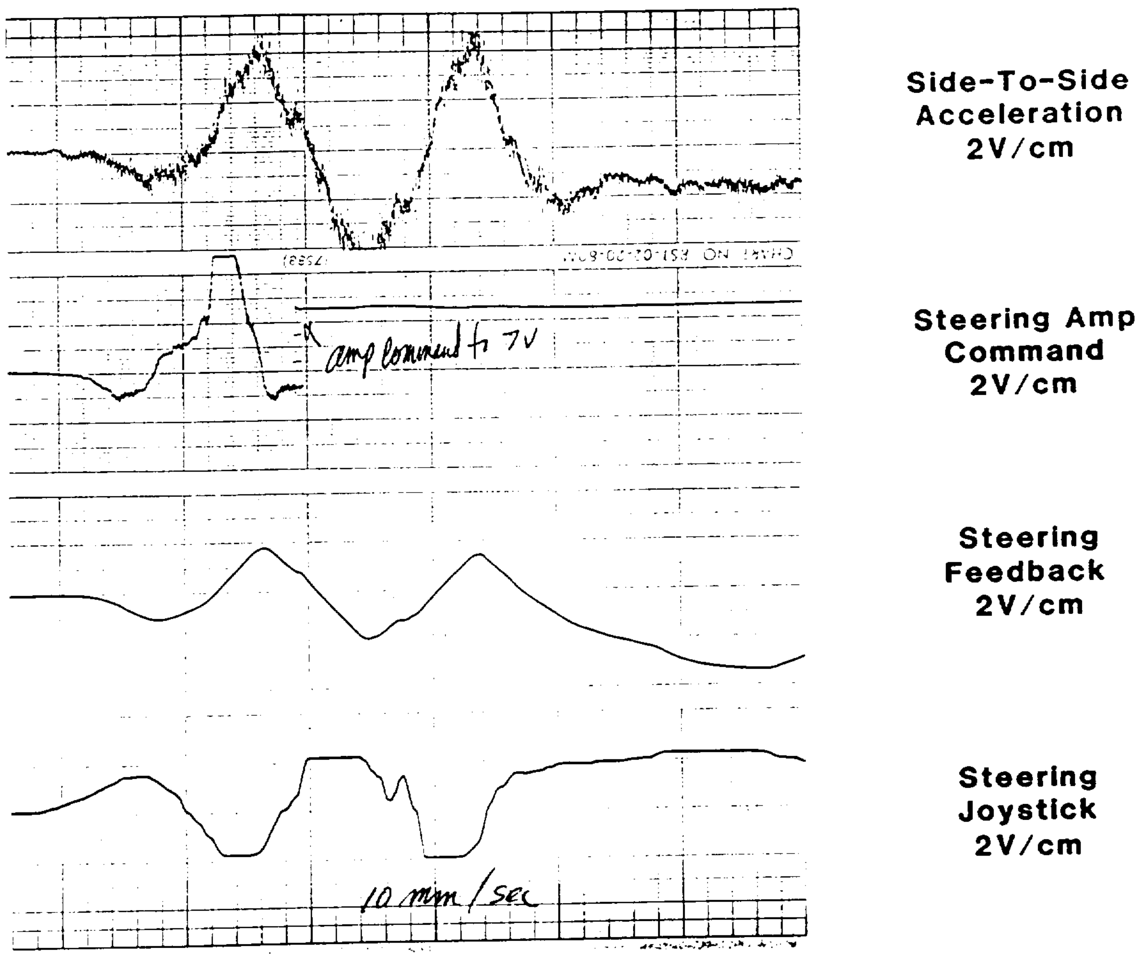


FIGURE C-32. TEST 3.1.1.2(C)

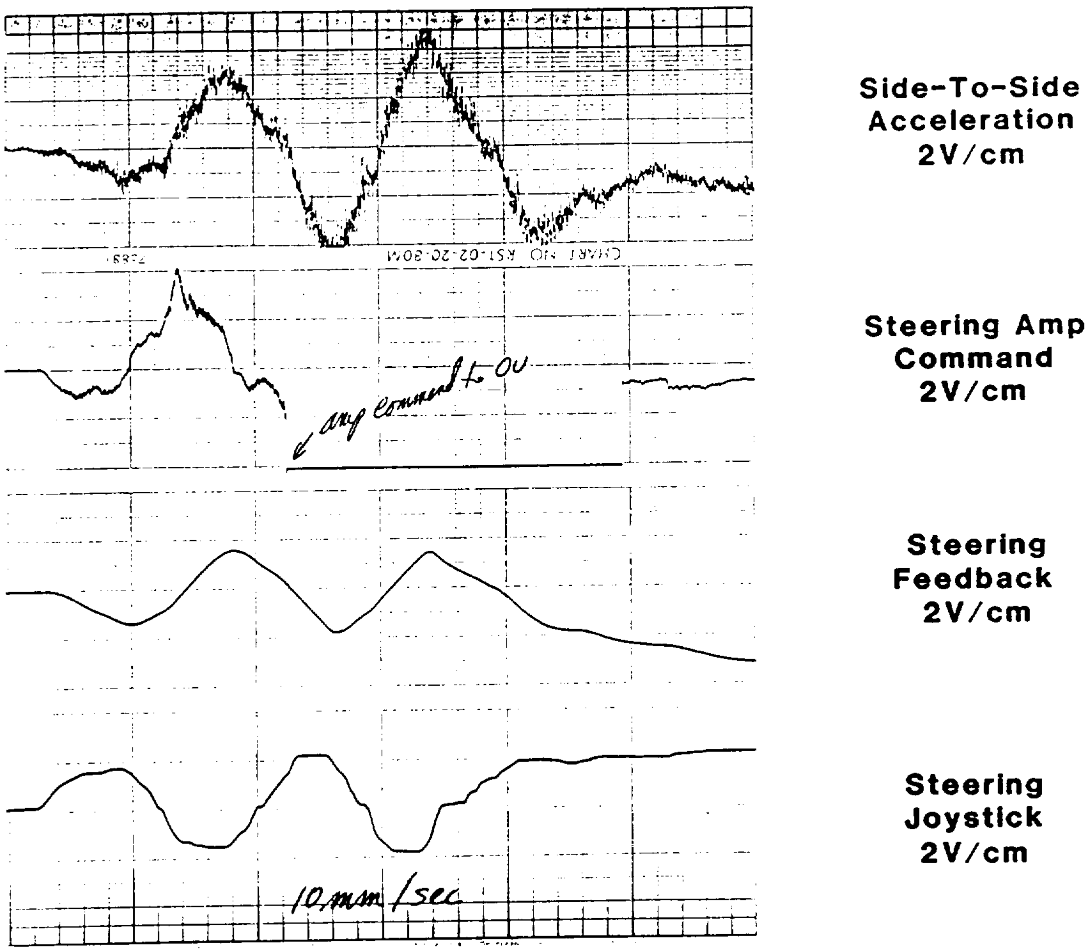


FIGURE C-33. TEST 3.1.1.2(D)

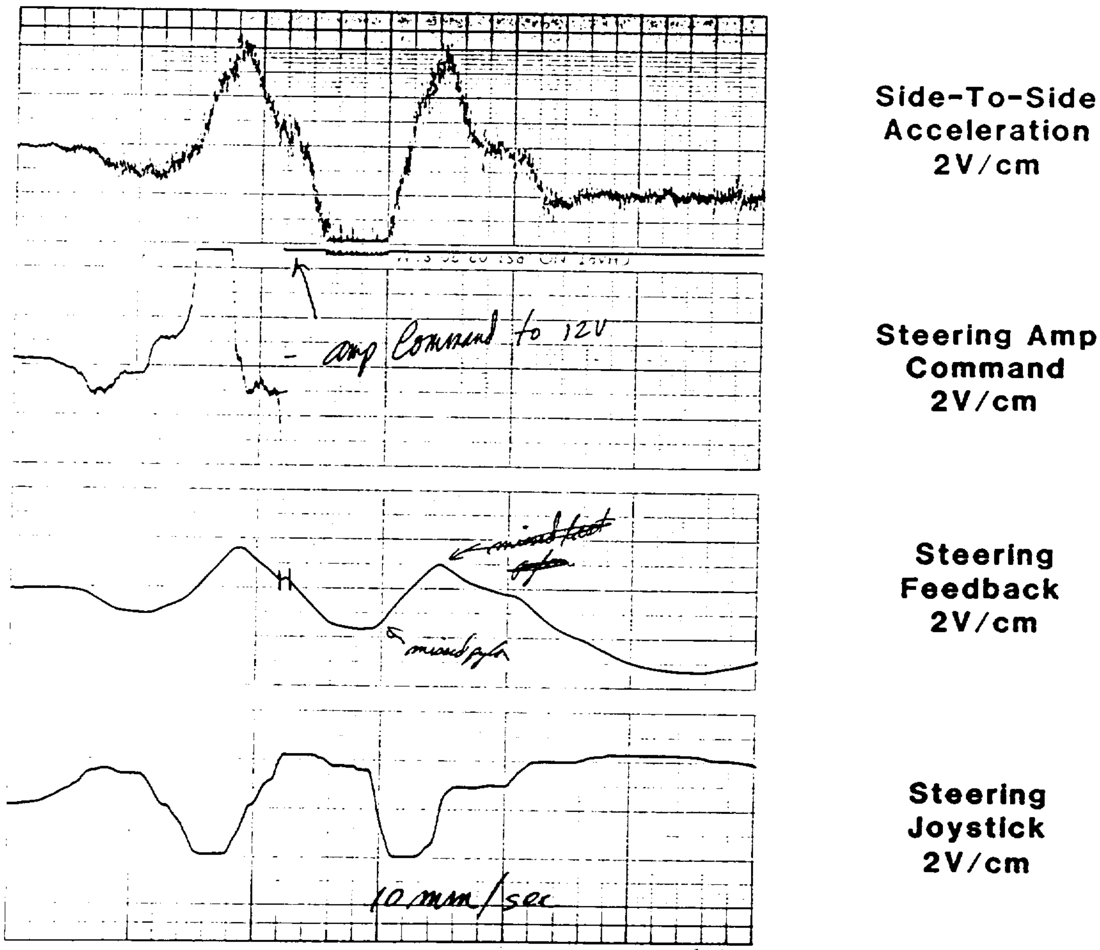
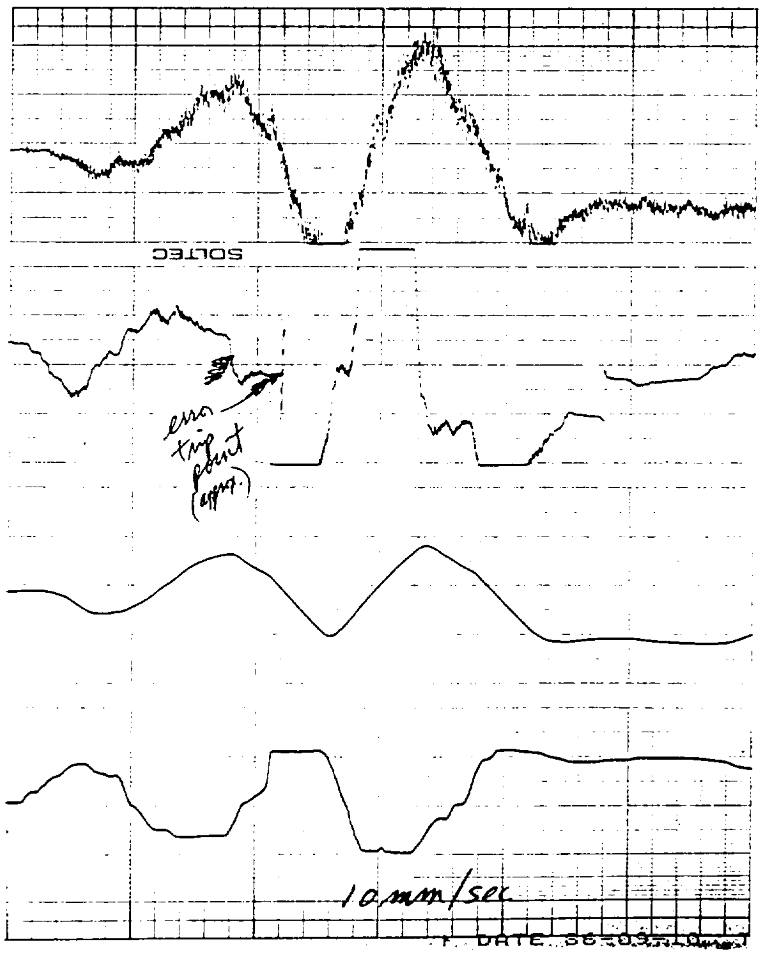


FIGURE C-34. TEST 3.1.1.2(E)



Side-To-Side Acceleration 2V/cm

Steering Amp Command 2V/cm

Steering Feedback 2V/cm

Steering Joystick 2V/cm

FIGURE C-35. TEST 3.1.1.3

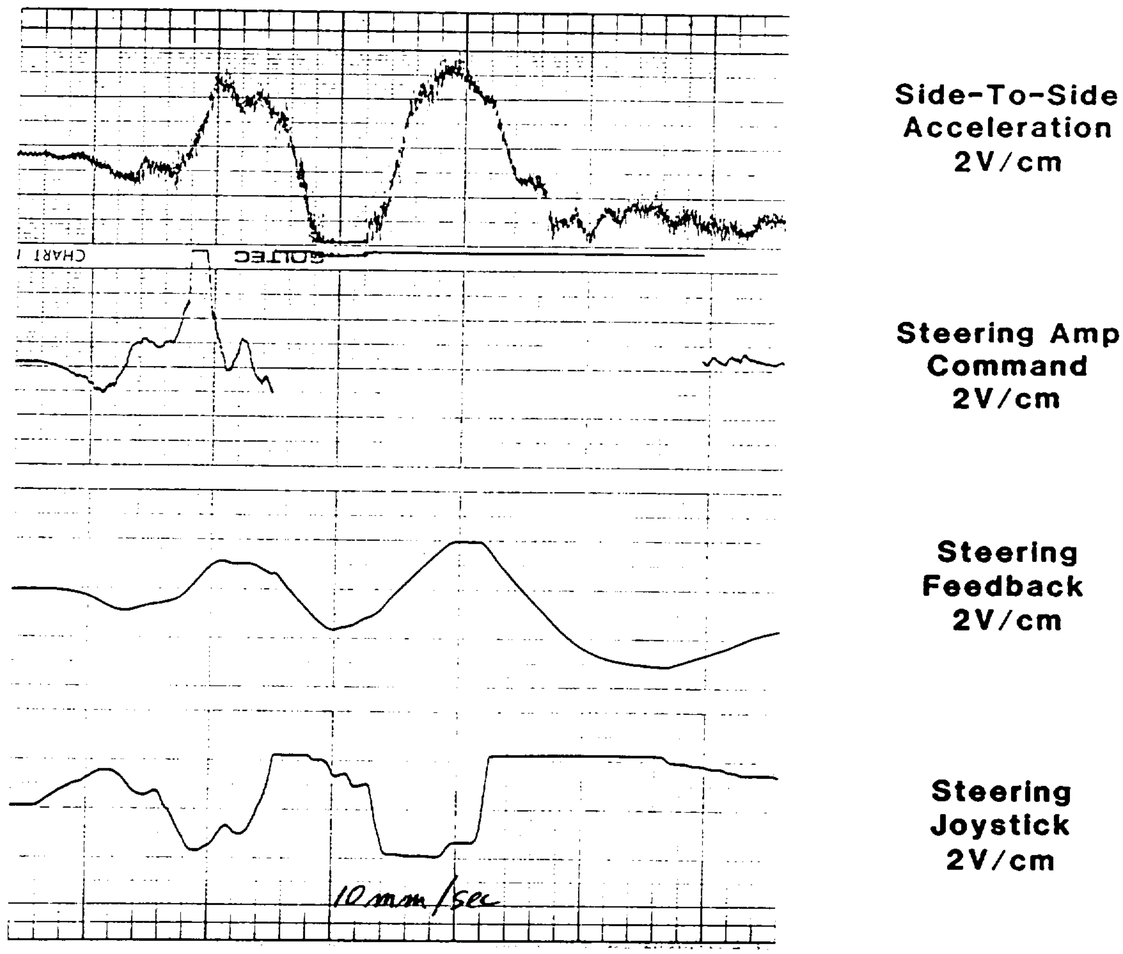


FIGURE C-36. TEST 3.1.1.4(A)

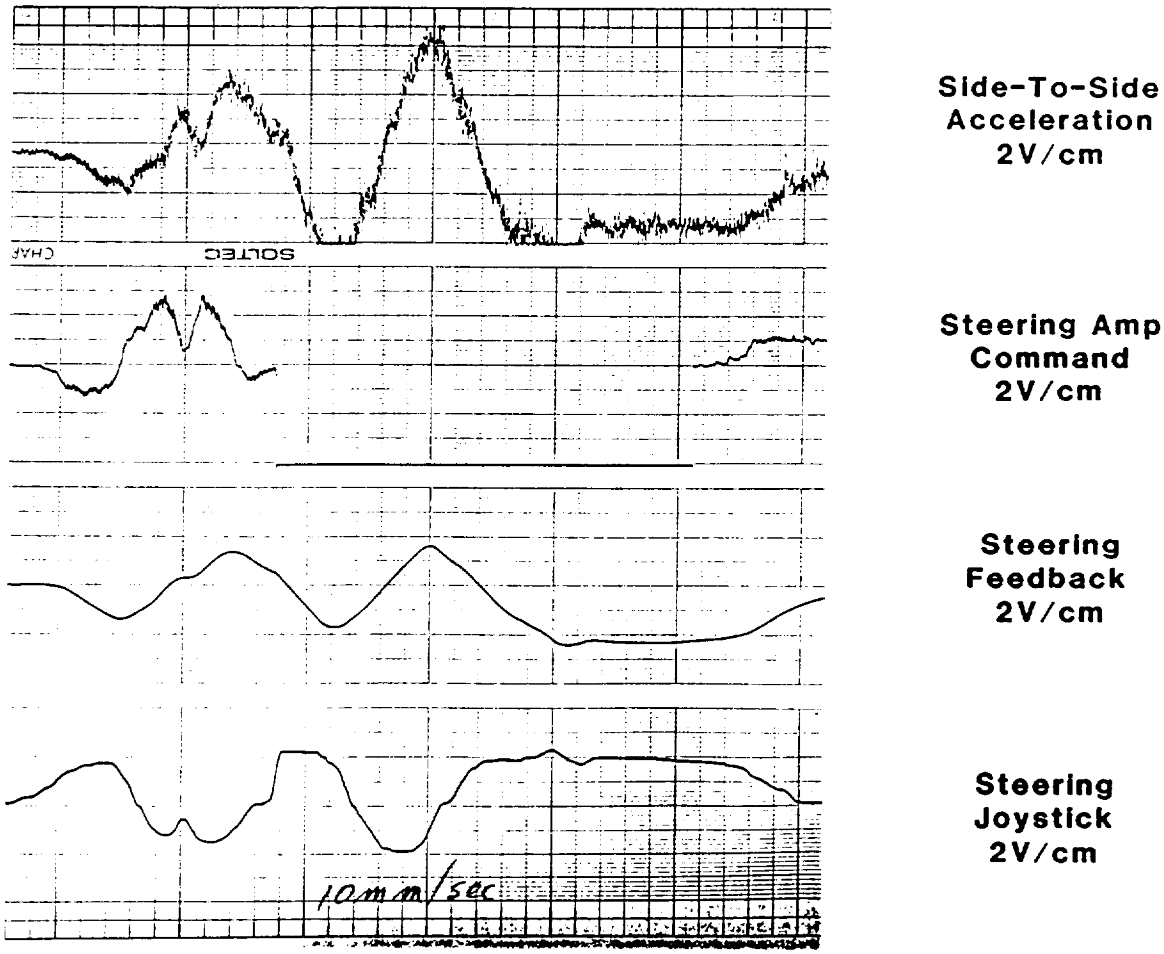


FIGURE C-37. TEST 3.1.1.4(B)

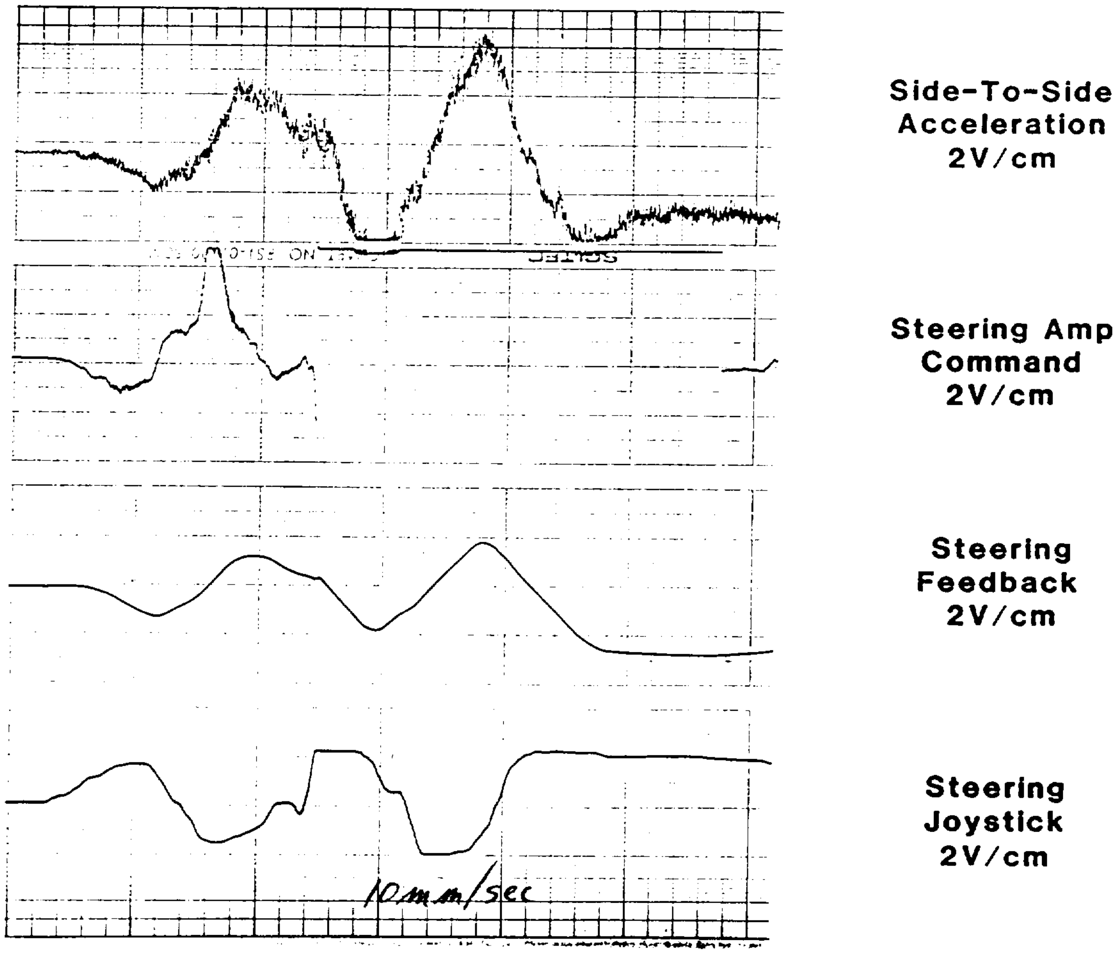
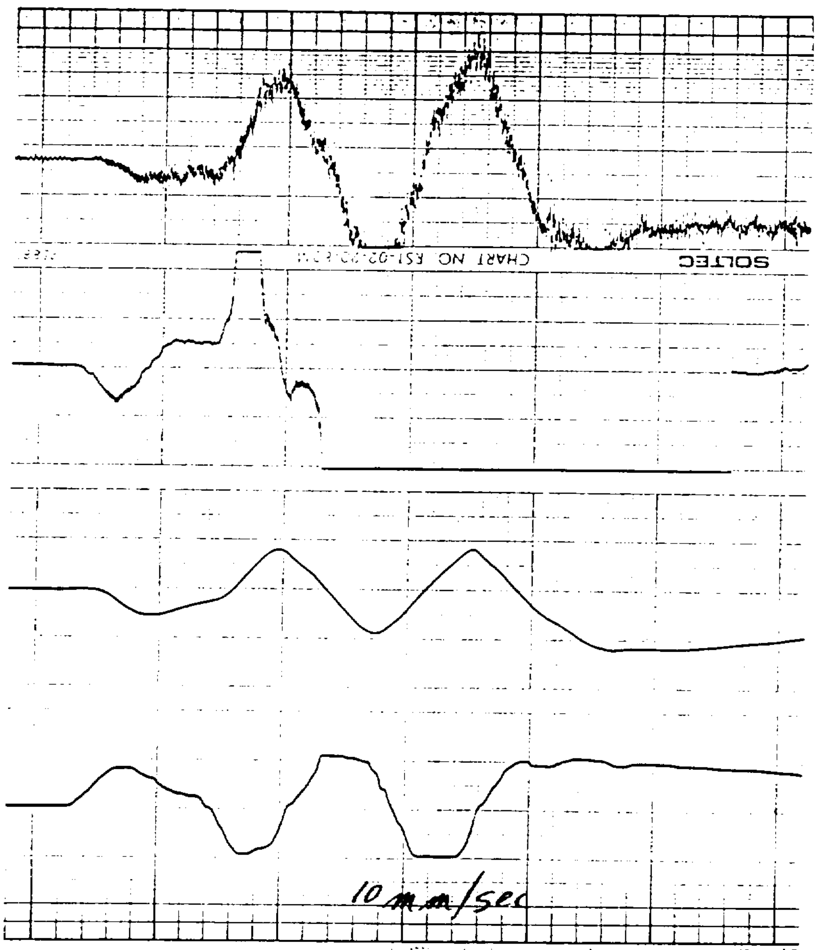


FIGURE C-38. TEST 3.1.1.4(C)



Side-To-Side Acceleration 2V/cm

Steering Amp Command 2V/cm

Steering Feedback 2V/cm

Steering Joystick 2V/cm

FIGURE C-39. TEST 3.1.1.5(A)

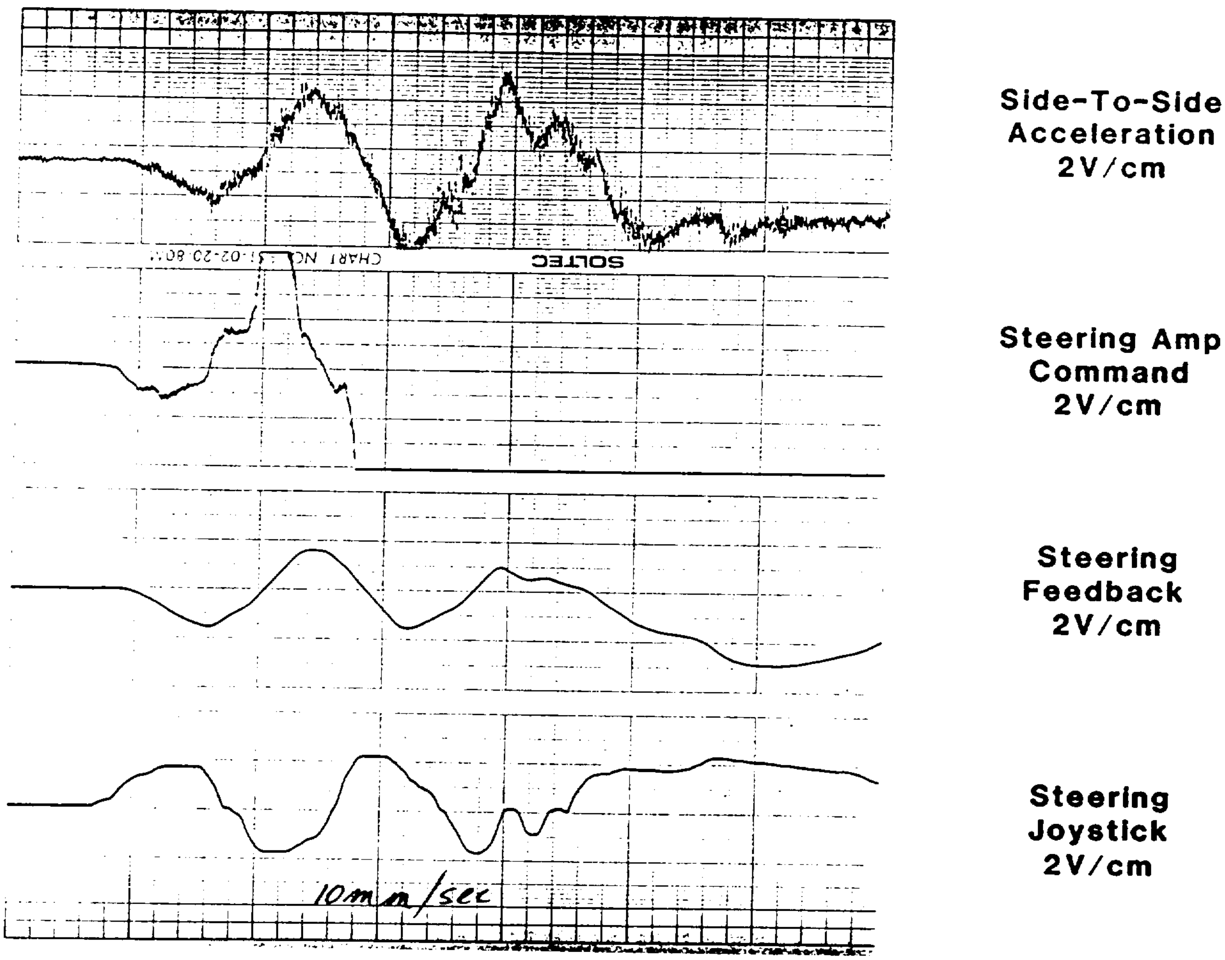


FIGURE C-40. TEST 3.1.1.5(B)

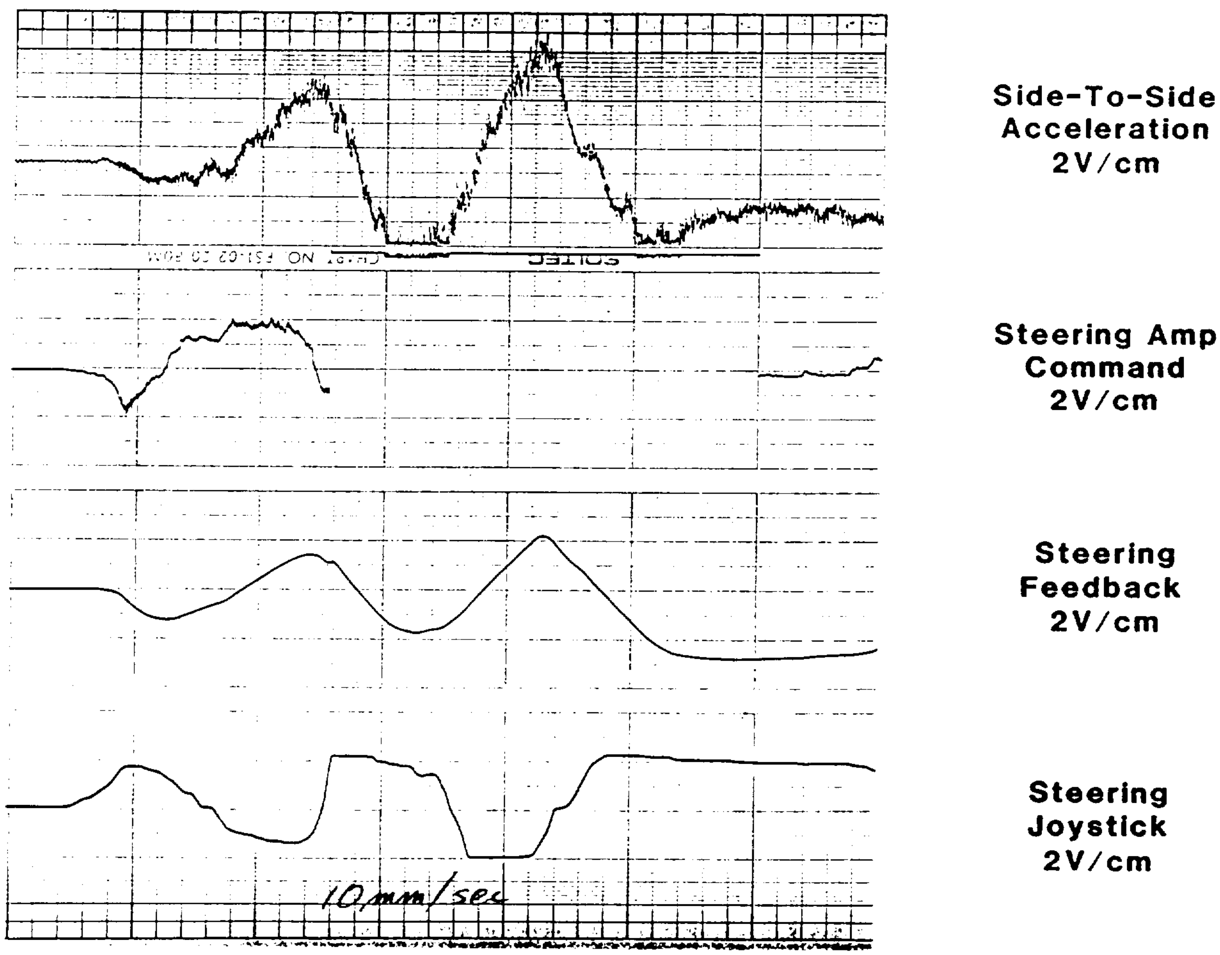


FIGURE C-41. TEST 3.1.1.5(C)

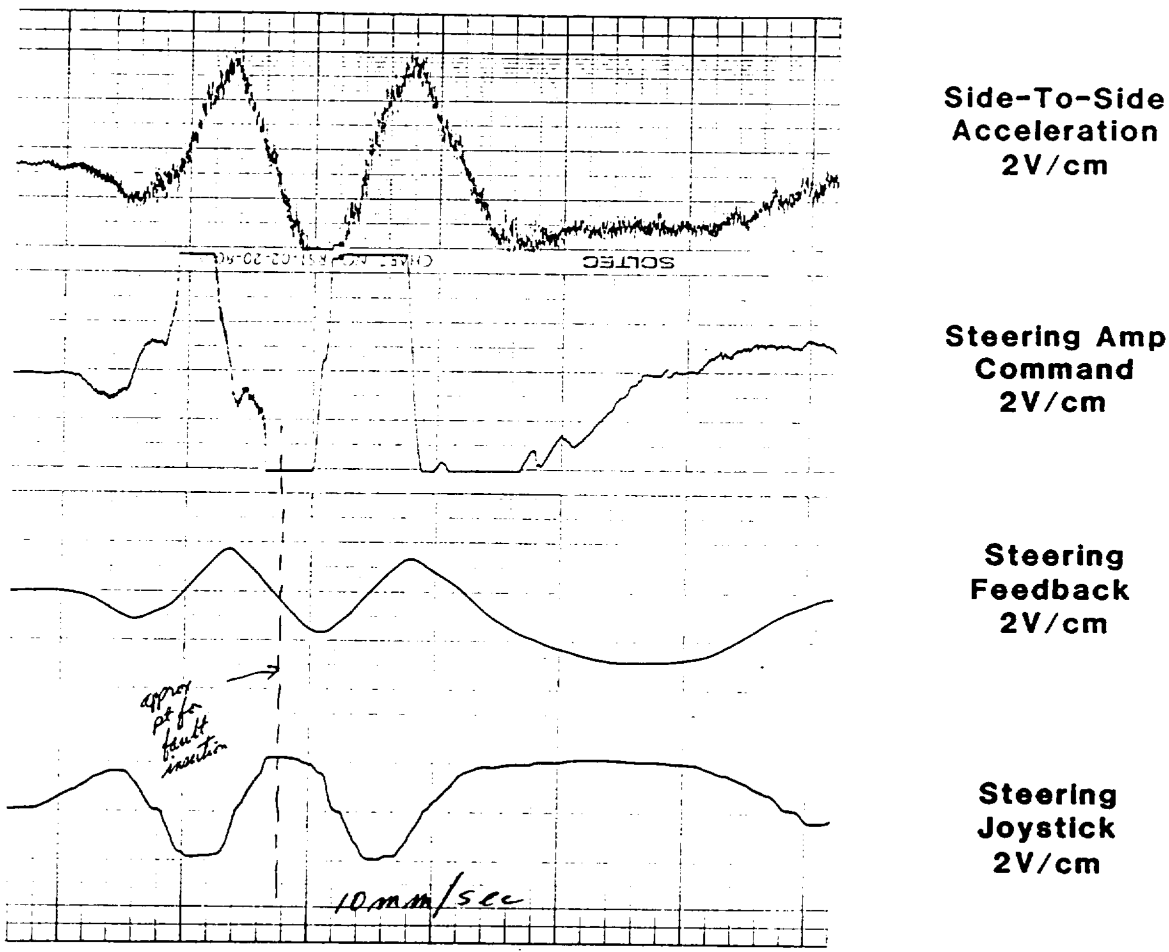


FIGURE C-42. TEST 3.1.1.6

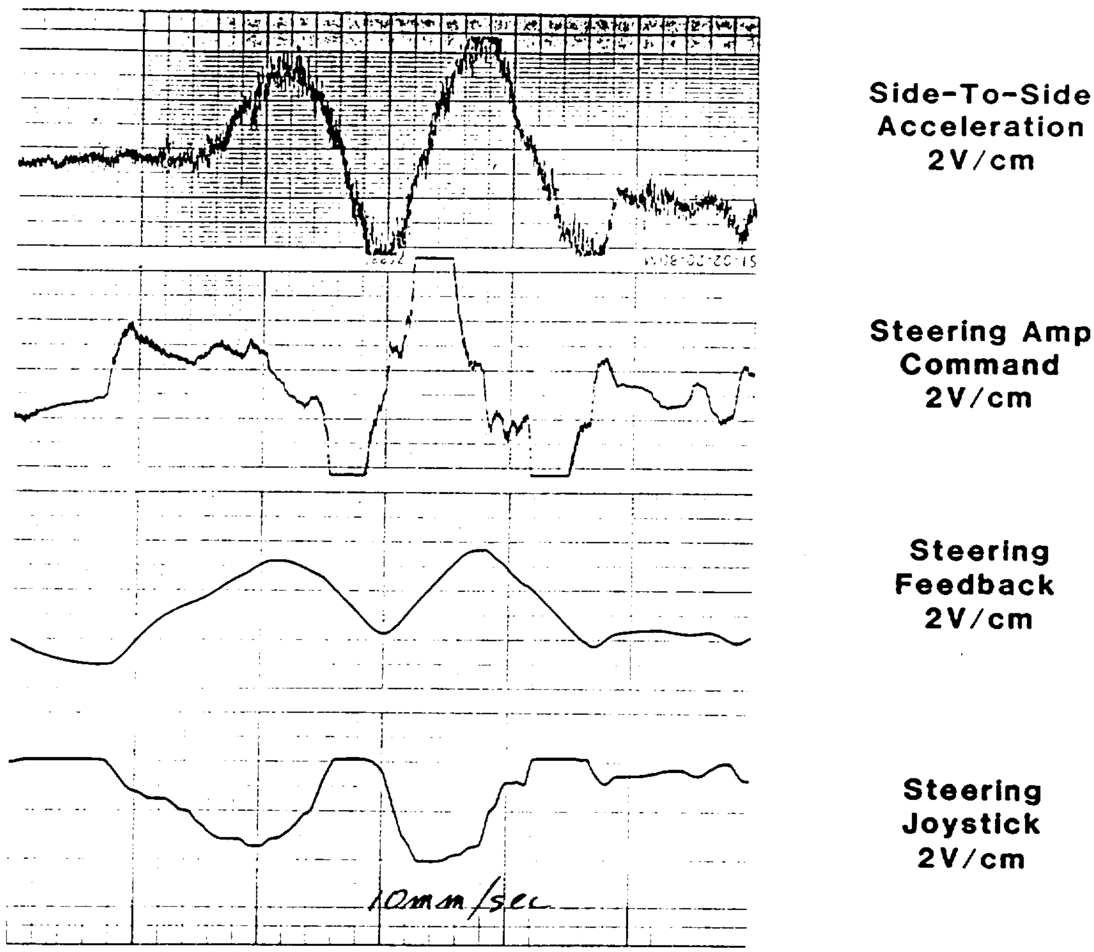


FIGURE C-43. TEST 3.1.1.7

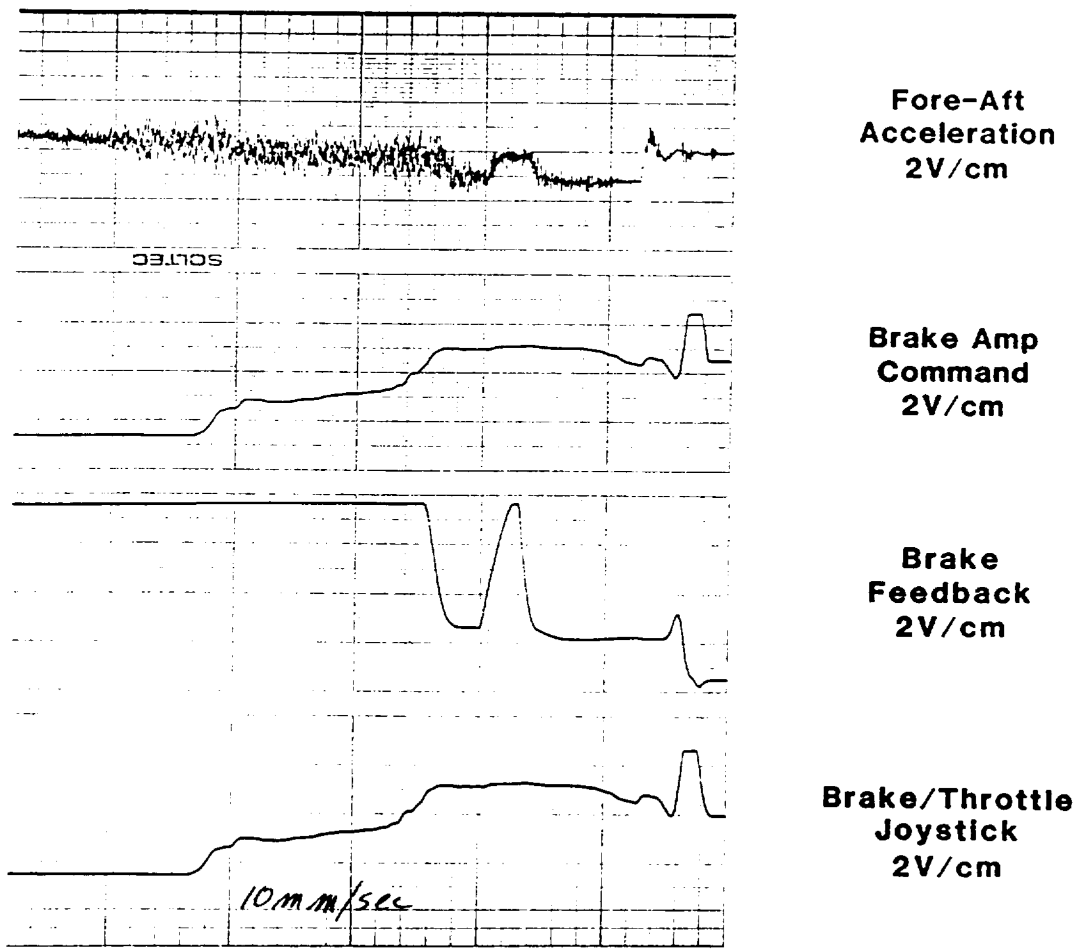


FIGURE C-44. TEST 3.1.2.1

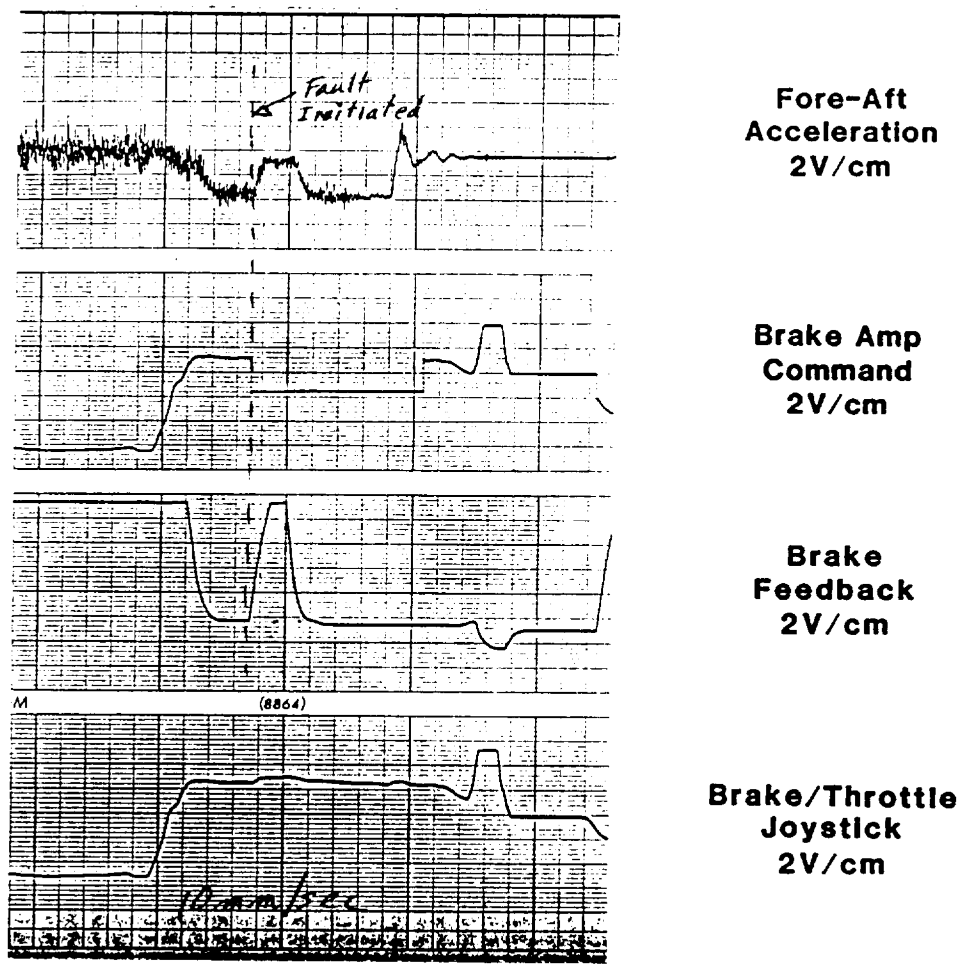


FIGURE C-45. TEST 3.1.2.2(A)

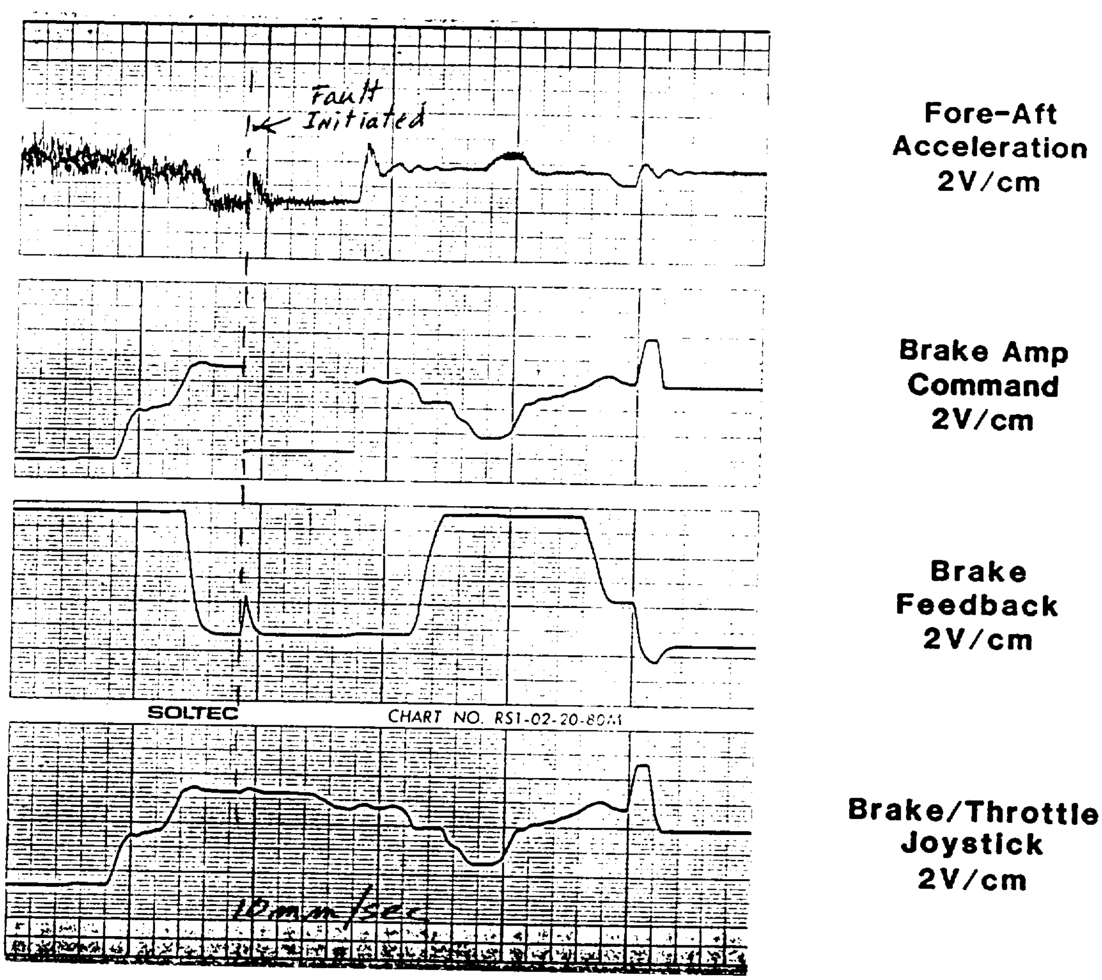


FIGURE C-46. TEST 3.1.2.2(B)

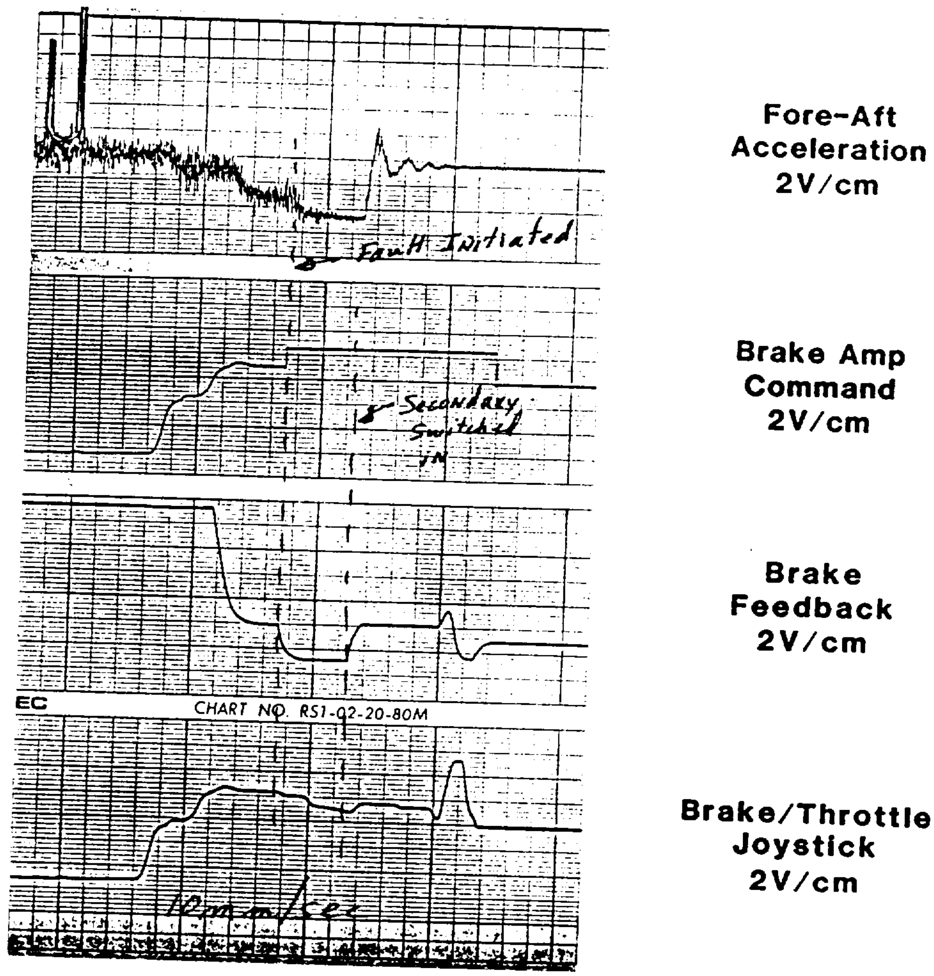


FIGURE C-47. TEST 3.1.2.2(C)

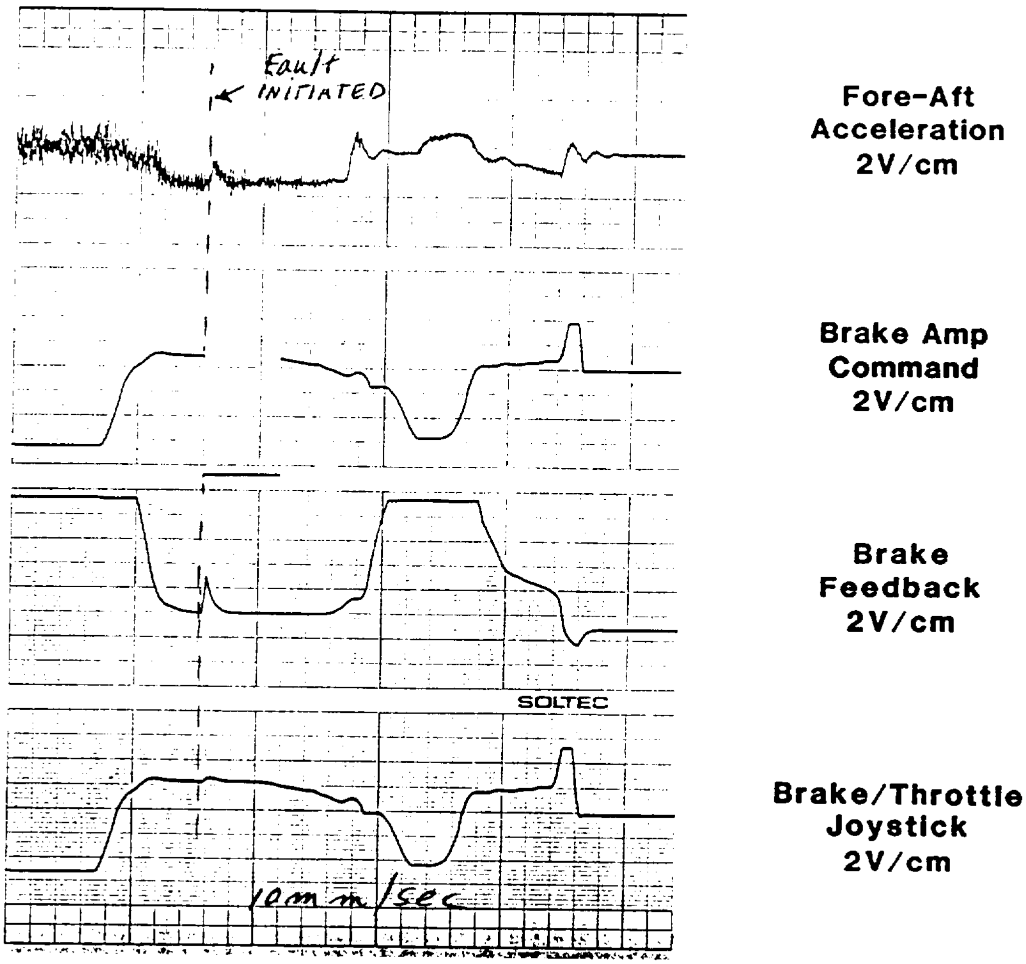


FIGURE C-48. TEST 3.1.2.2(D)

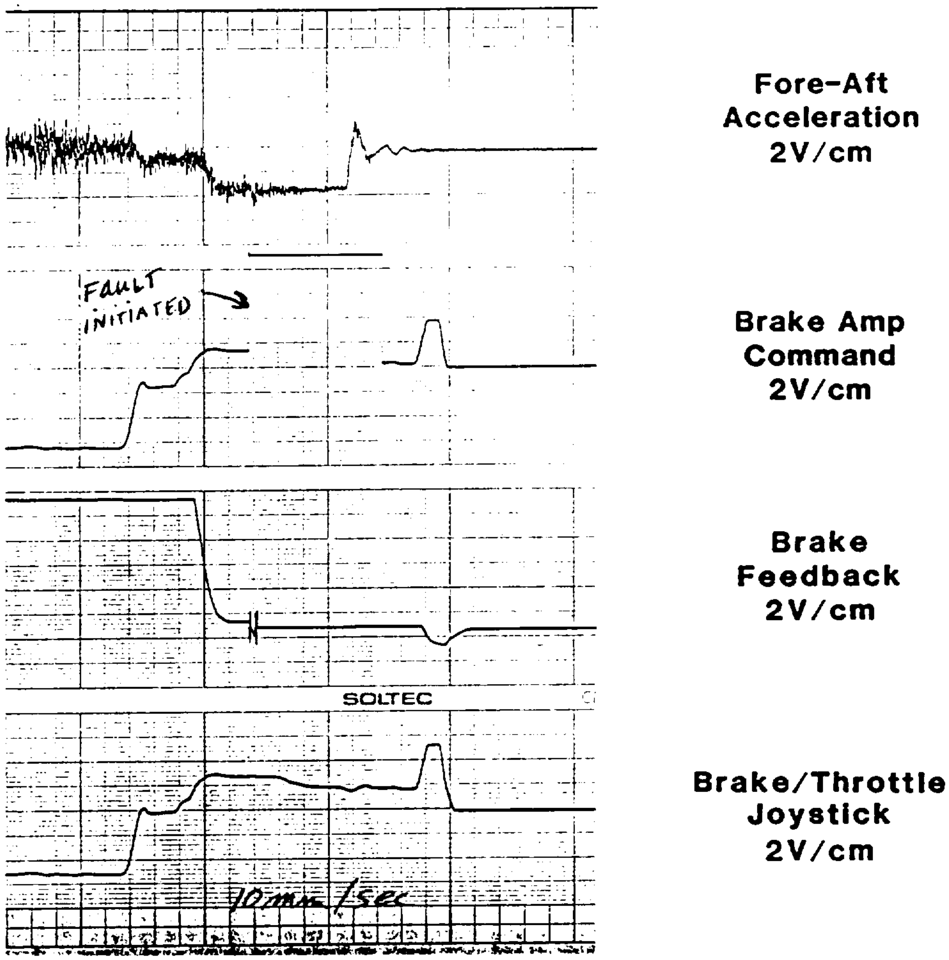


FIGURE C-49. TEST 3.1.2.2(E)

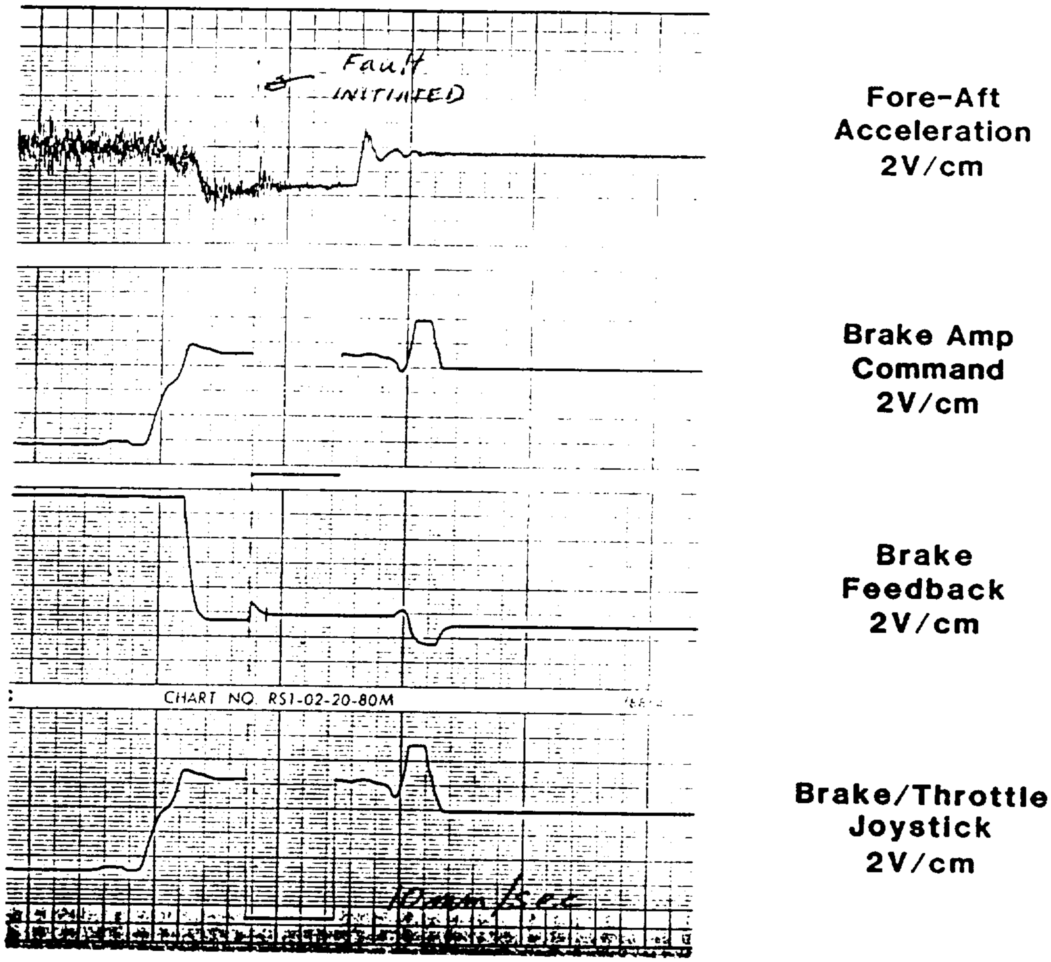
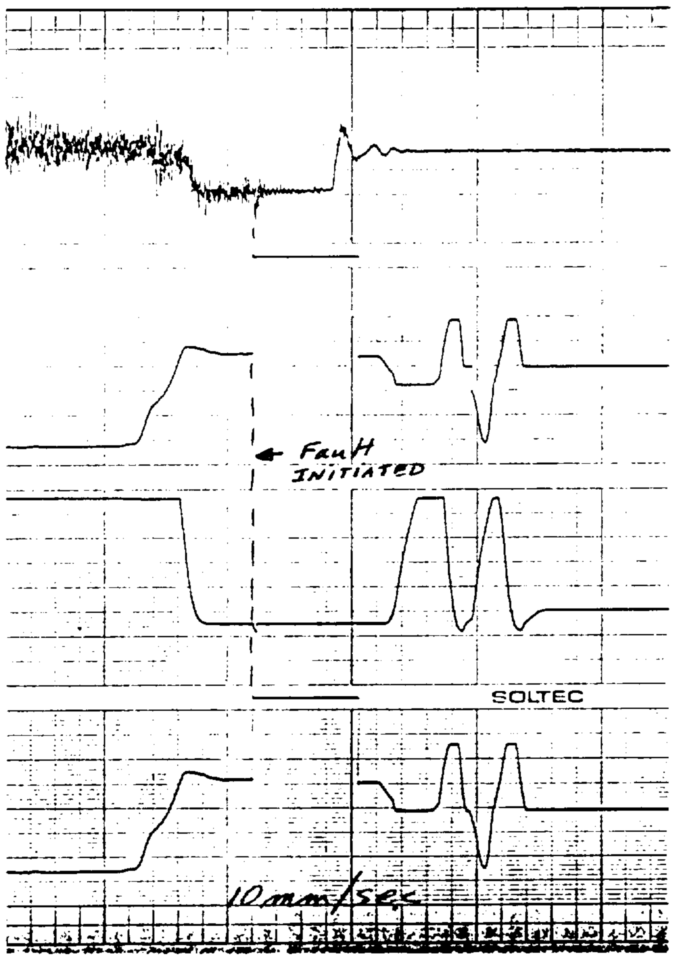


FIGURE C-50. TEST 3.1.2.3(A)



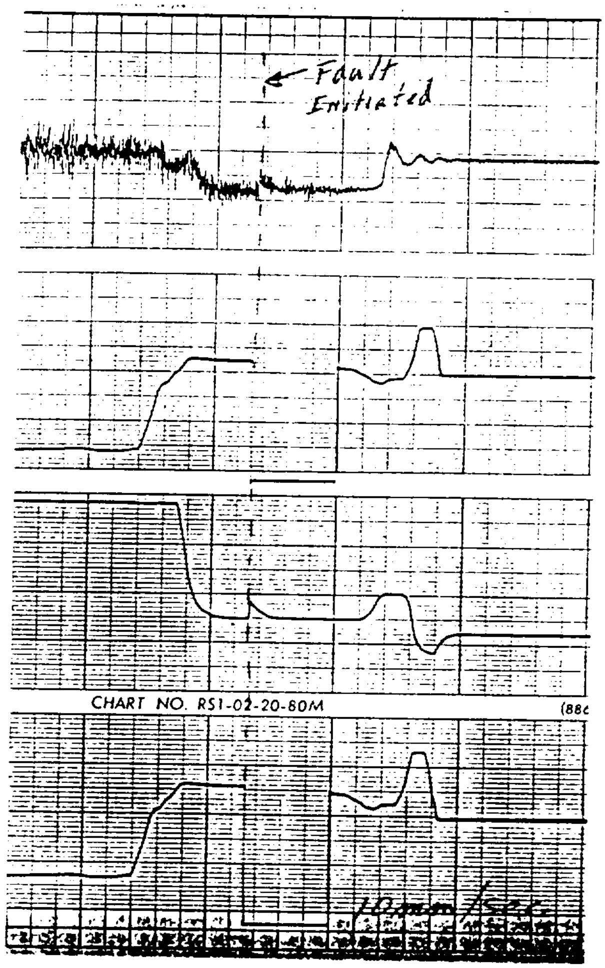
Fore-Aft
Acceleration
2V/cm

Brake Amp
Command
2V/cm

Brake
Feedback
2V/cm

Brake/Throttle
Joystick
2V/cm

FIGURE C-51. TEST 3.1.2.3(B)



Fore-Aft Acceleration 2V/cm

Brake Amp Command 2V/cm

Brake Feedback 2V/cm

Brake/Throttle Joystick 2V/cm

FIGURE C-52. TEST 3.1.2.3(C)

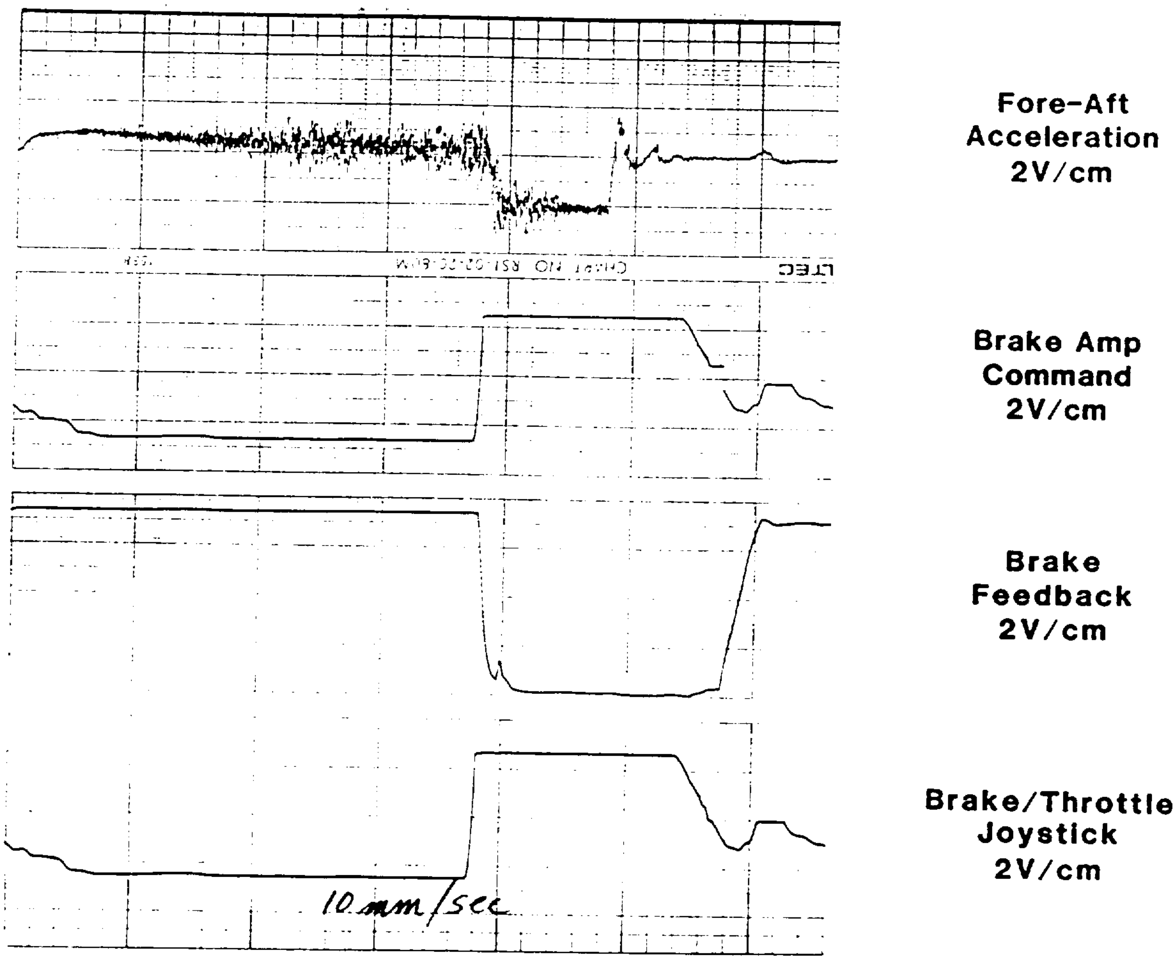


FIGURE C-53. TEST 3.1.3.1

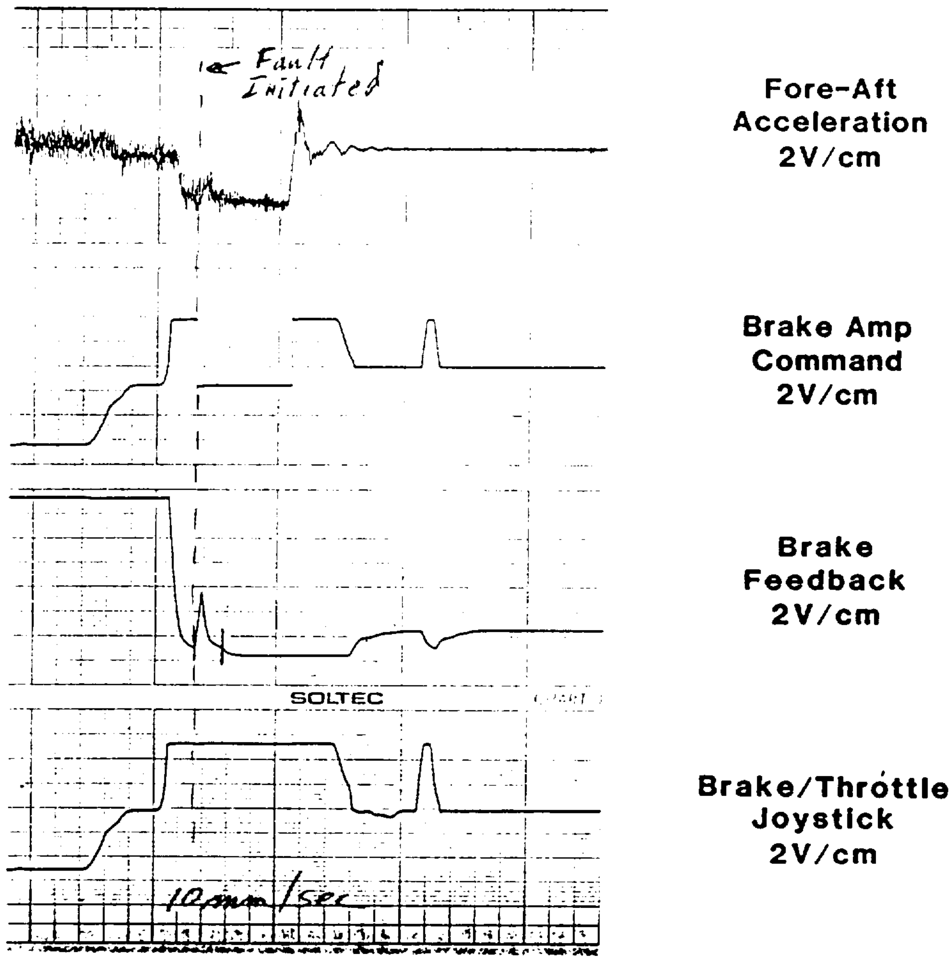


FIGURE C-54. TEST 3.1.3.2(A)

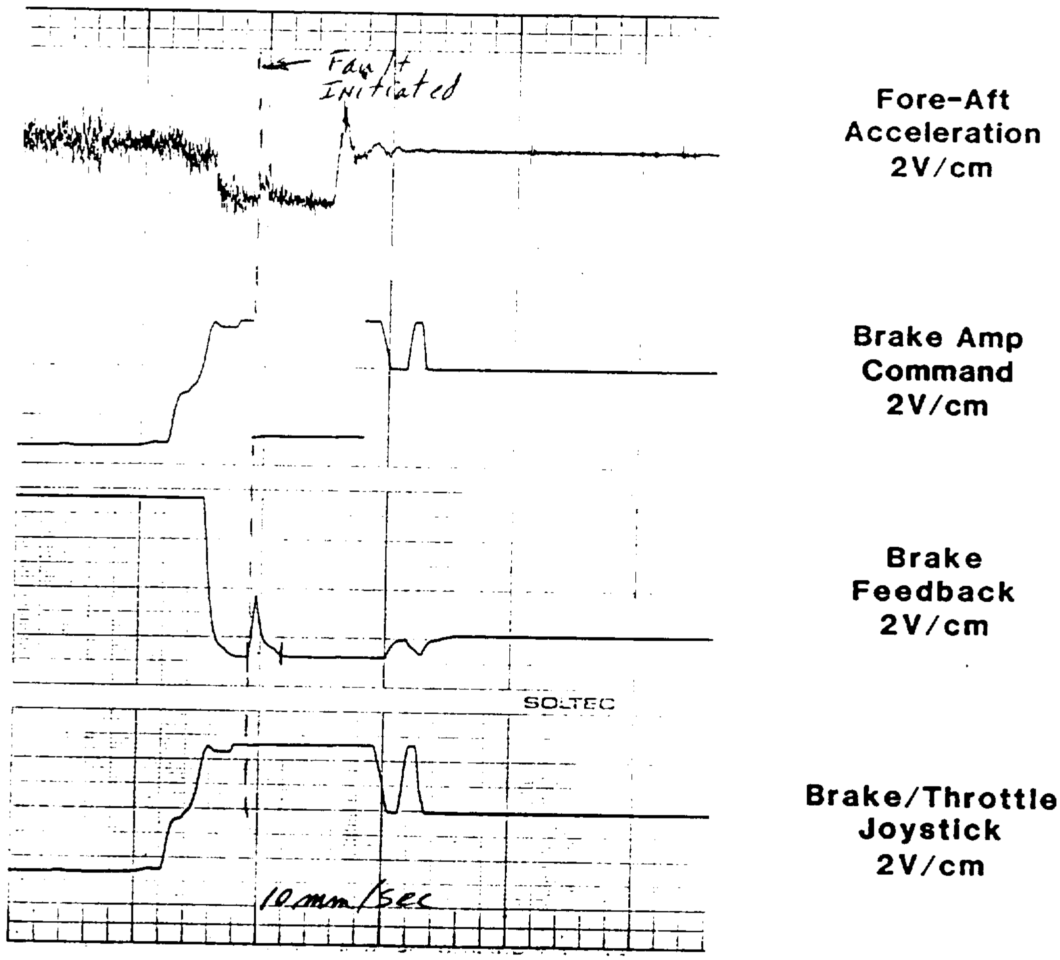


FIGURE C-55. TEST 3.1.3.2(B)

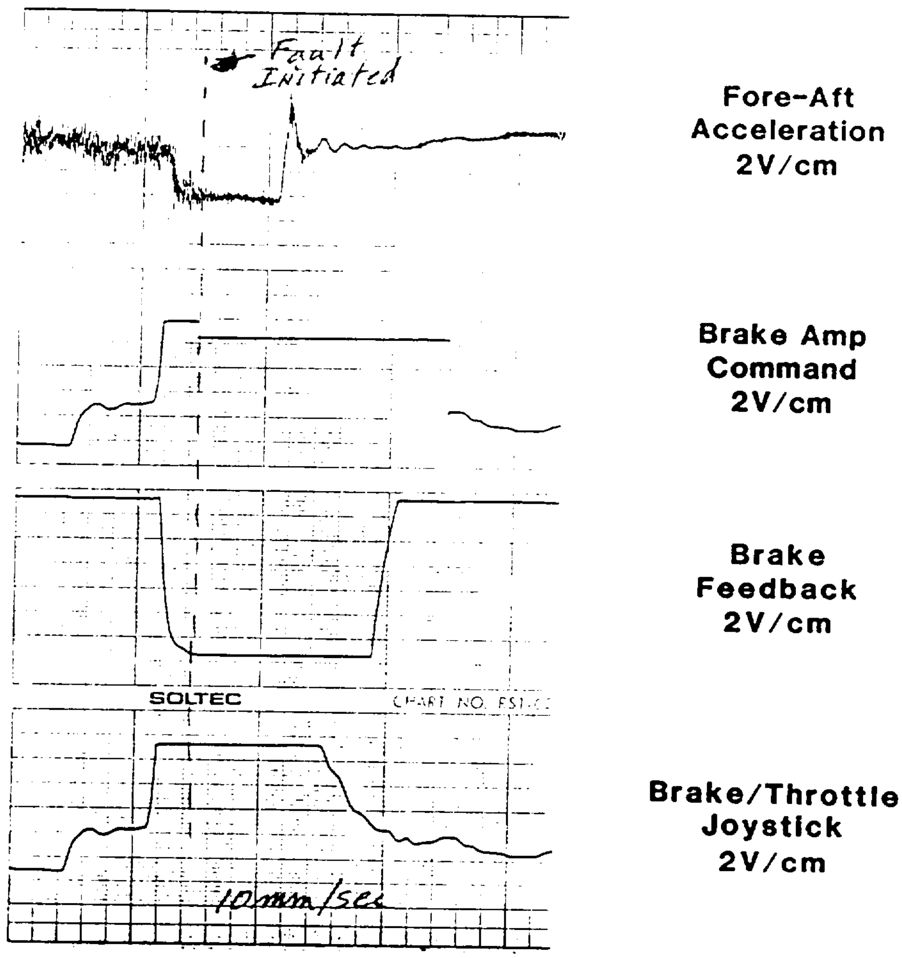


FIGURE C-56. TEST 3.1.3.2(C)

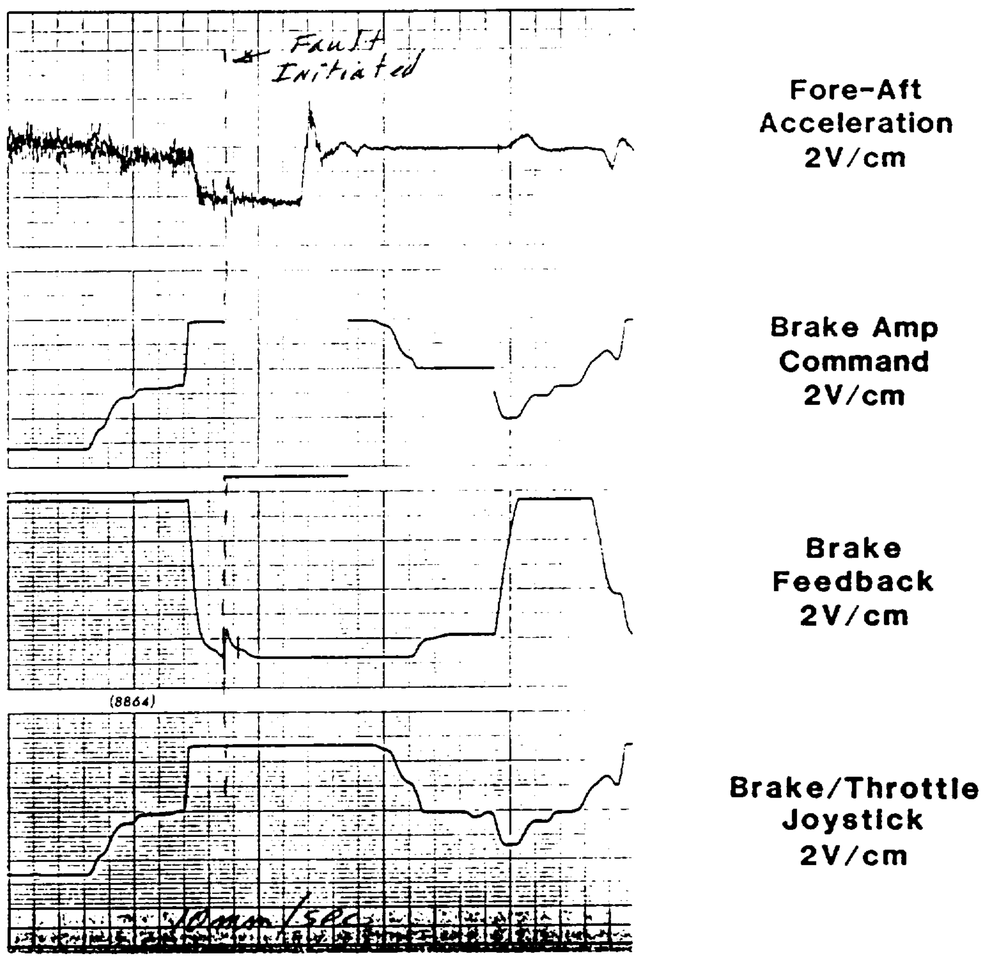


FIGURE C-57. TEST 3.1.3.2(D)

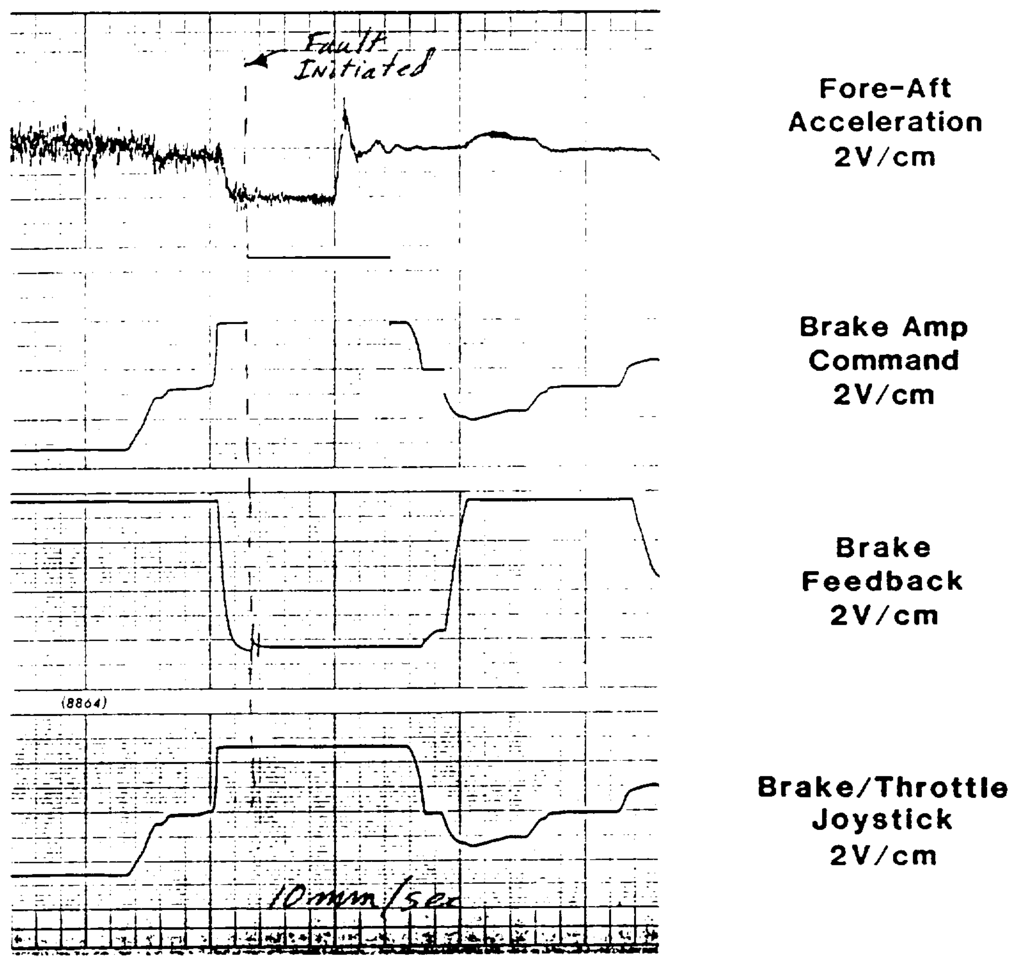


FIGURE C-58. TEST 3.1.3.2(E)

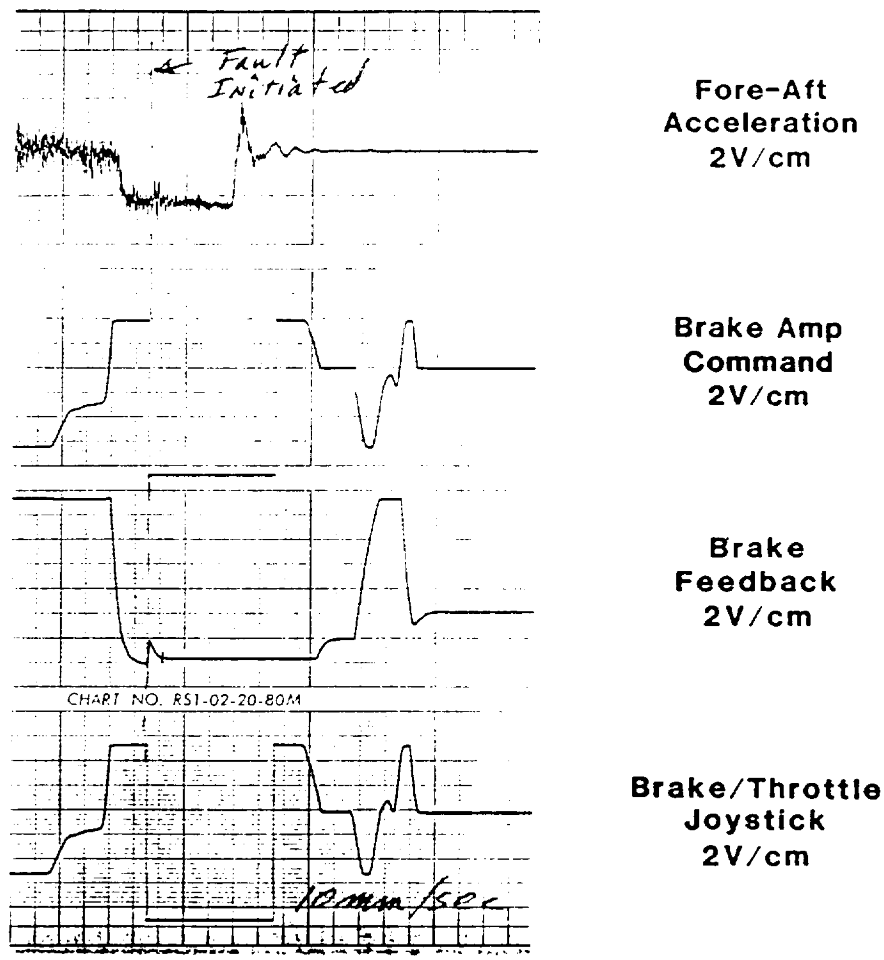


FIGURE C-59. TEST 3.1.3.3(A)

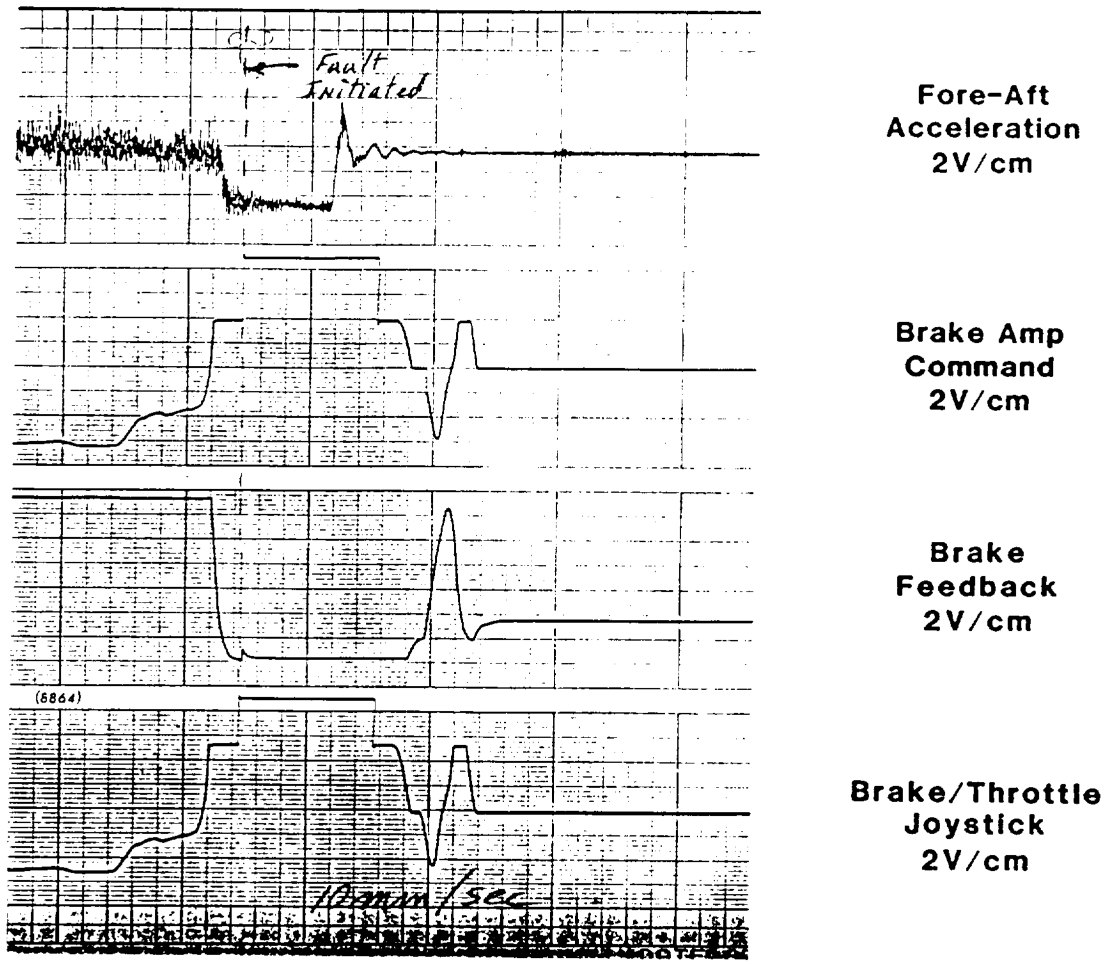


FIGURE C-60. TEST 3.1.3.3(B)

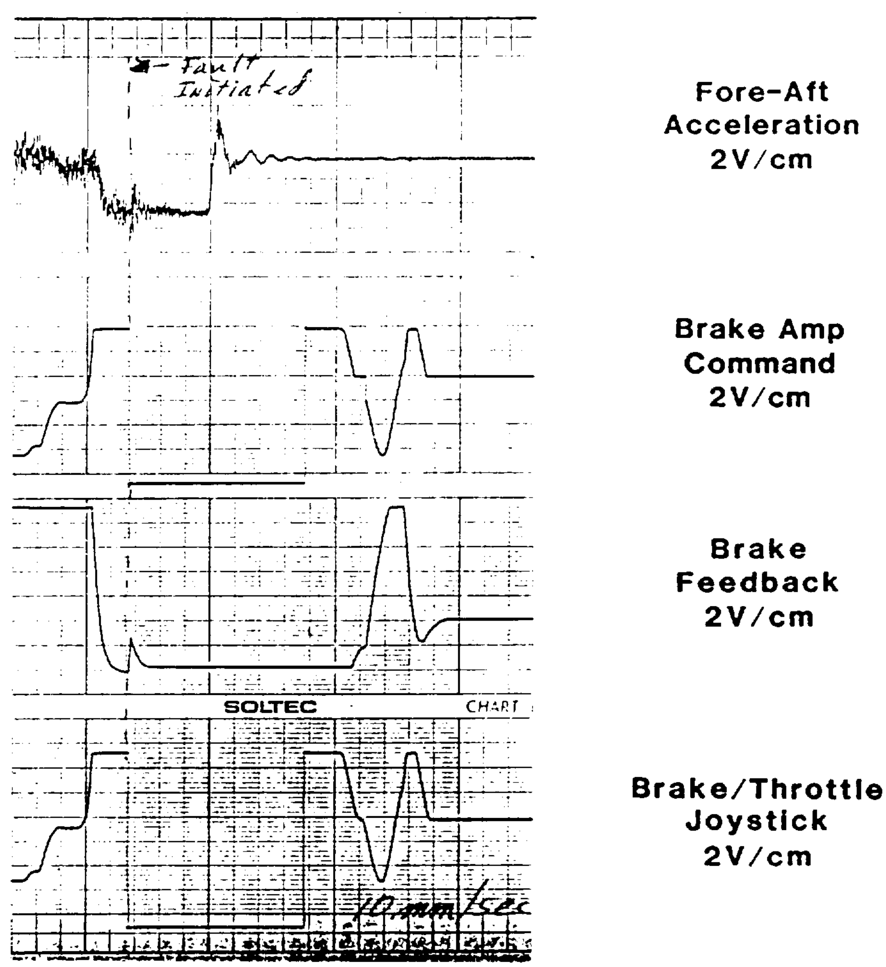
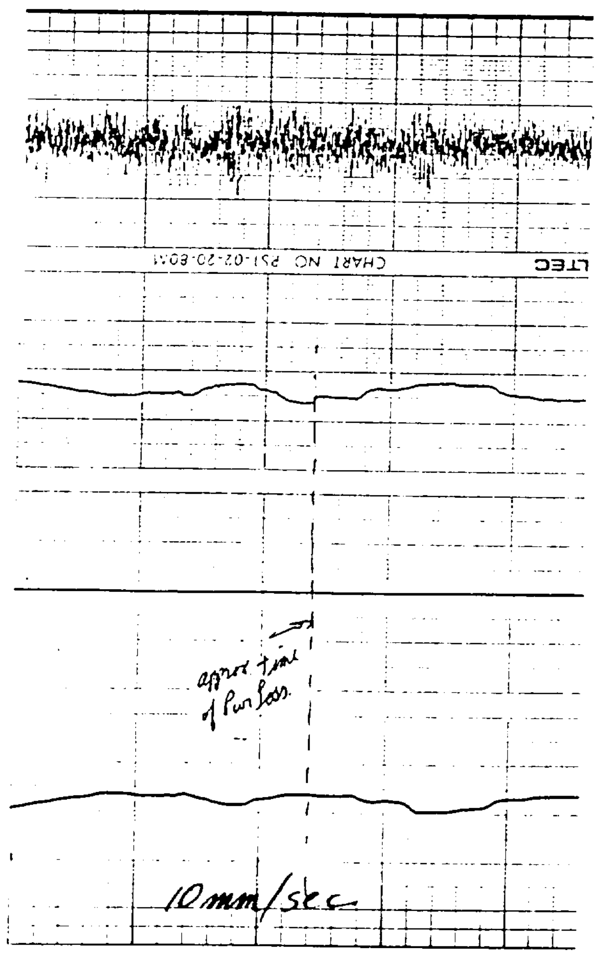


FIGURE C-61. TEST 3.1.3.3(C)



Side-To-Side Acceleration 2V/cm

Steering Amp Command 2V/cm

Steering Feedback 2V/cm

Steering Joystick 2V/cm

FIGURE C-62. TEST 3.2.1.1(A)

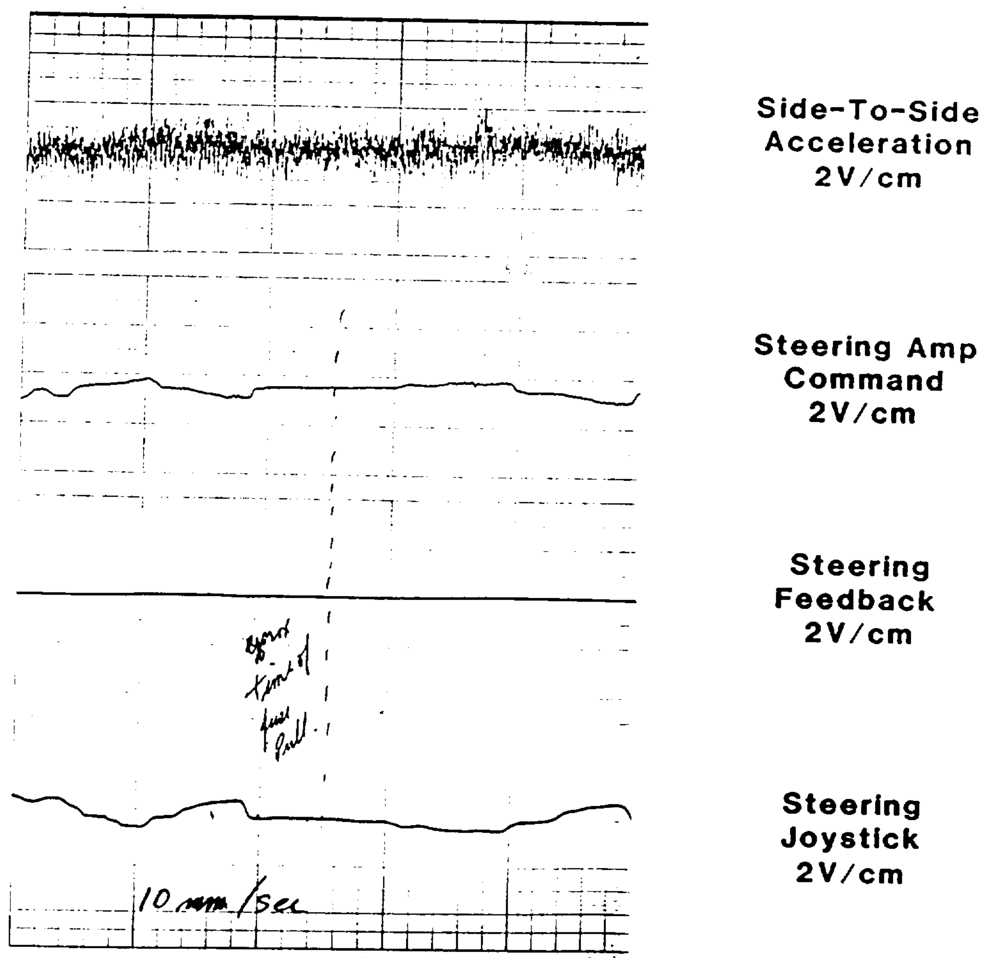
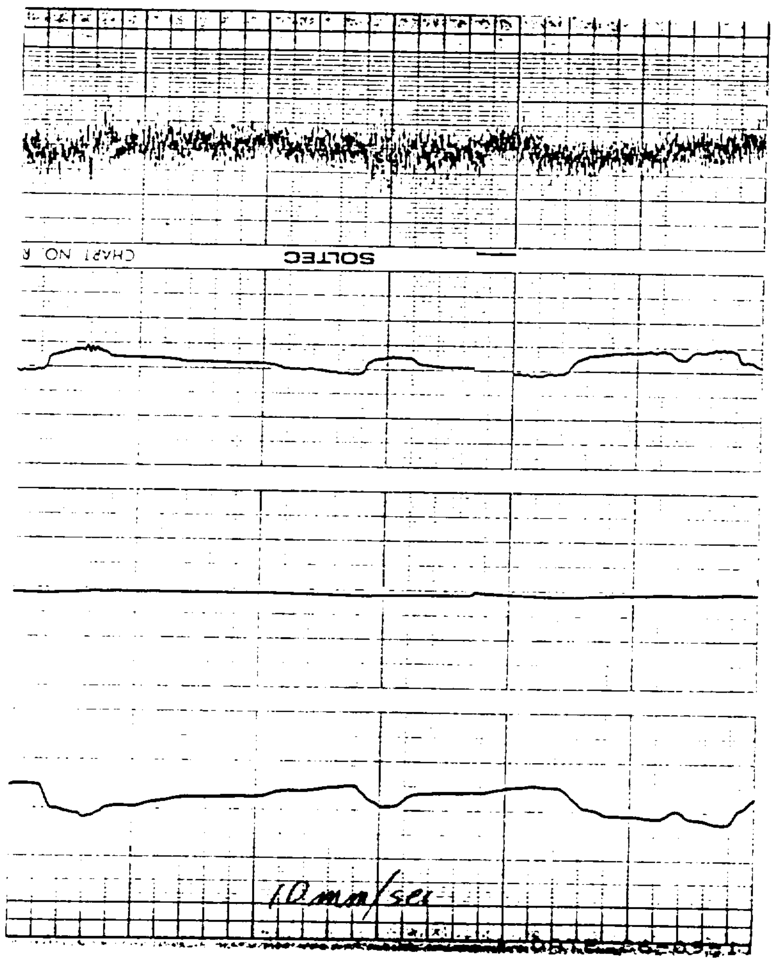


FIGURE C-63. TEST 3.2.1.1(B)



Side-To-Side Acceleration 2V/cm

Steering Amp Command 2V/cm

Steering Feedback 2V/cm

Steering Joystick 2V/cm

FIGURE C-64. TEST 3.2.1.2(E)

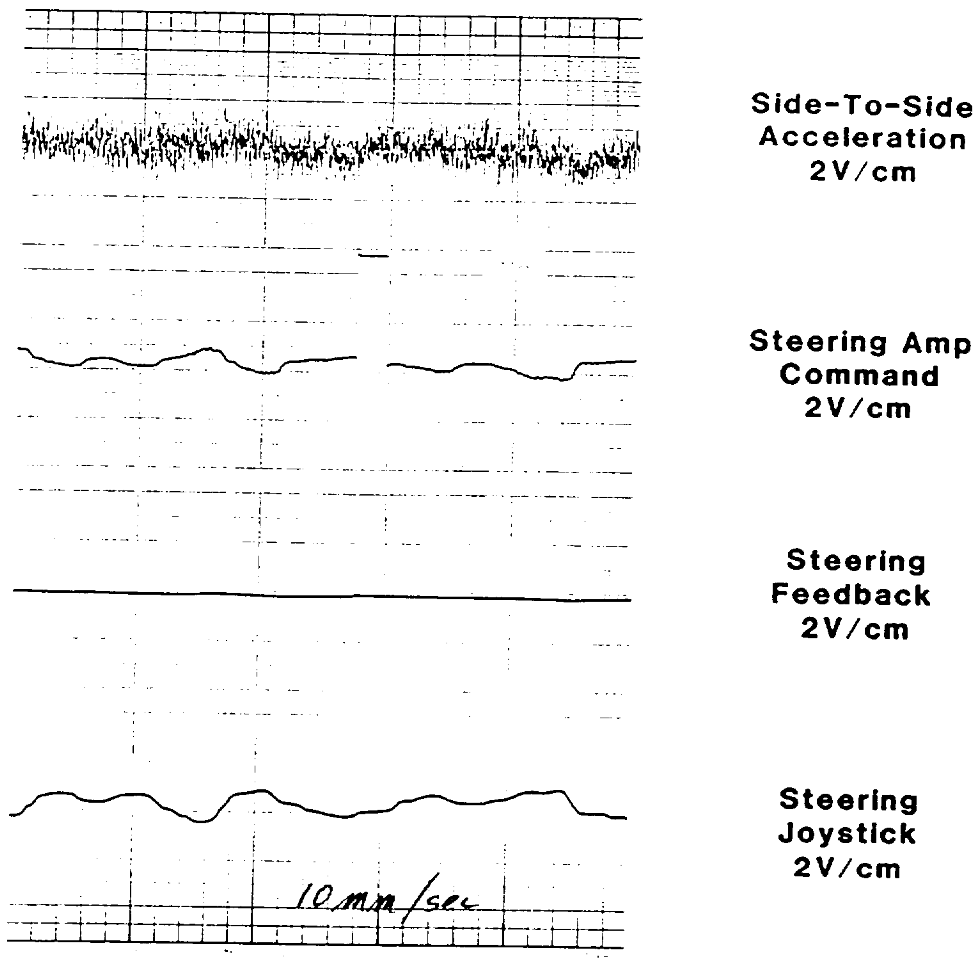


FIGURE C-65. TEST 3.2.1.2(J)

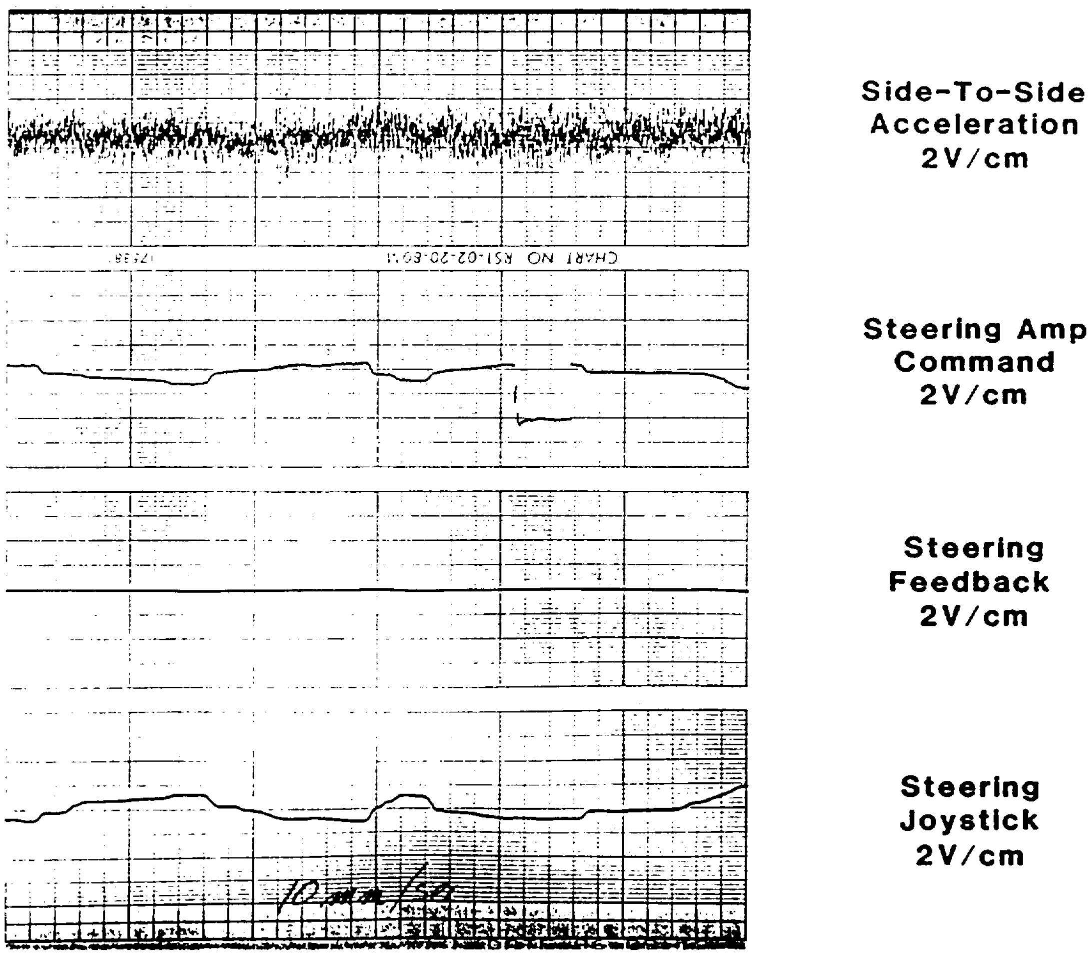


FIGURE C-66. TEST 3.2.1.3(B)

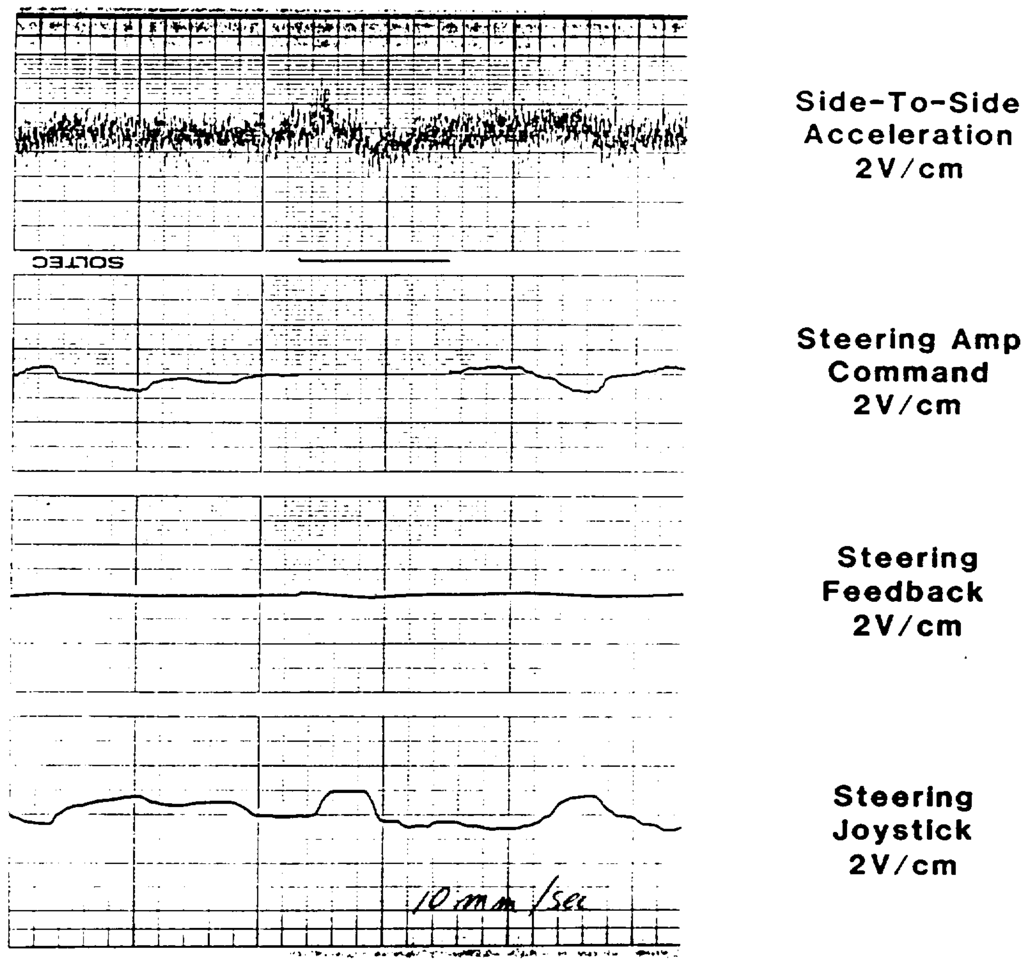


FIGURE C-67. TEST 3.2.1.4(A)

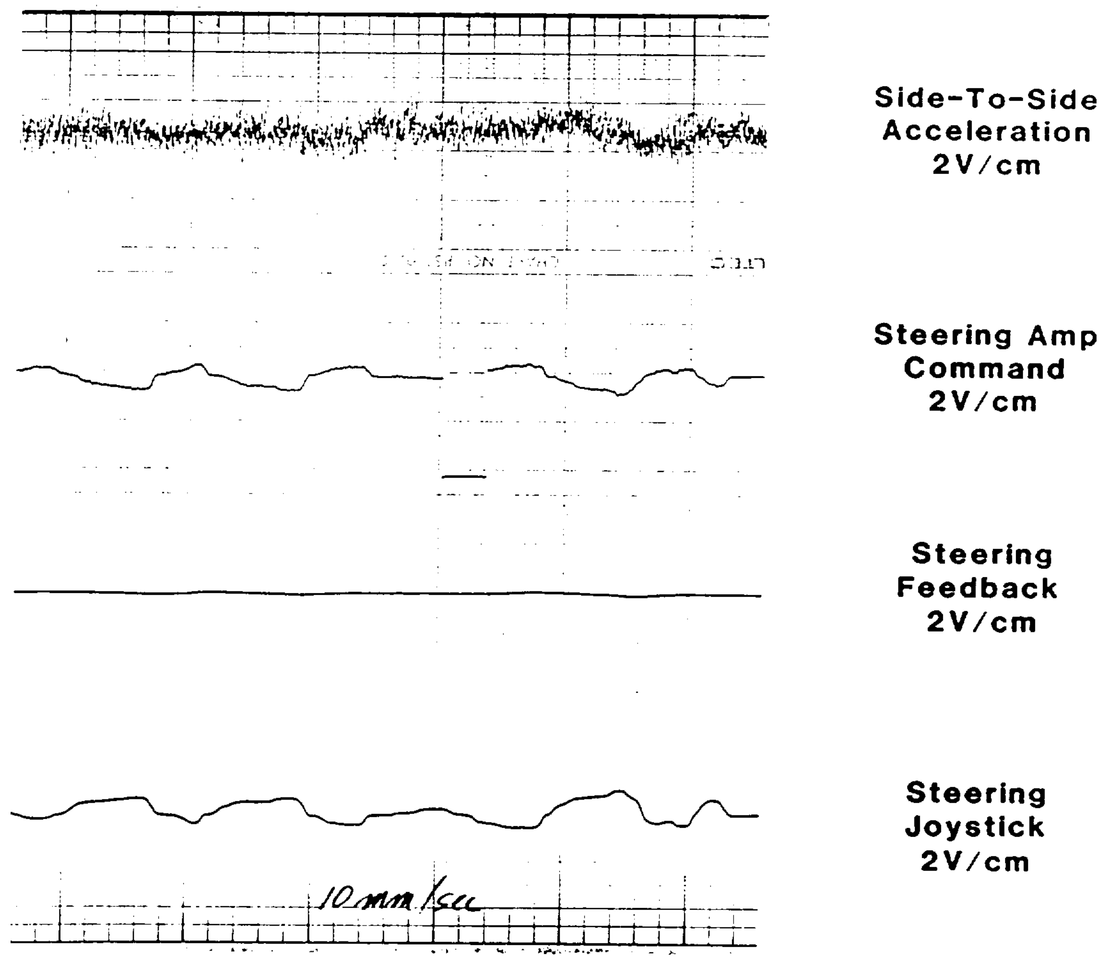


FIGURE C-68. TEST 3.2.1.4(B)

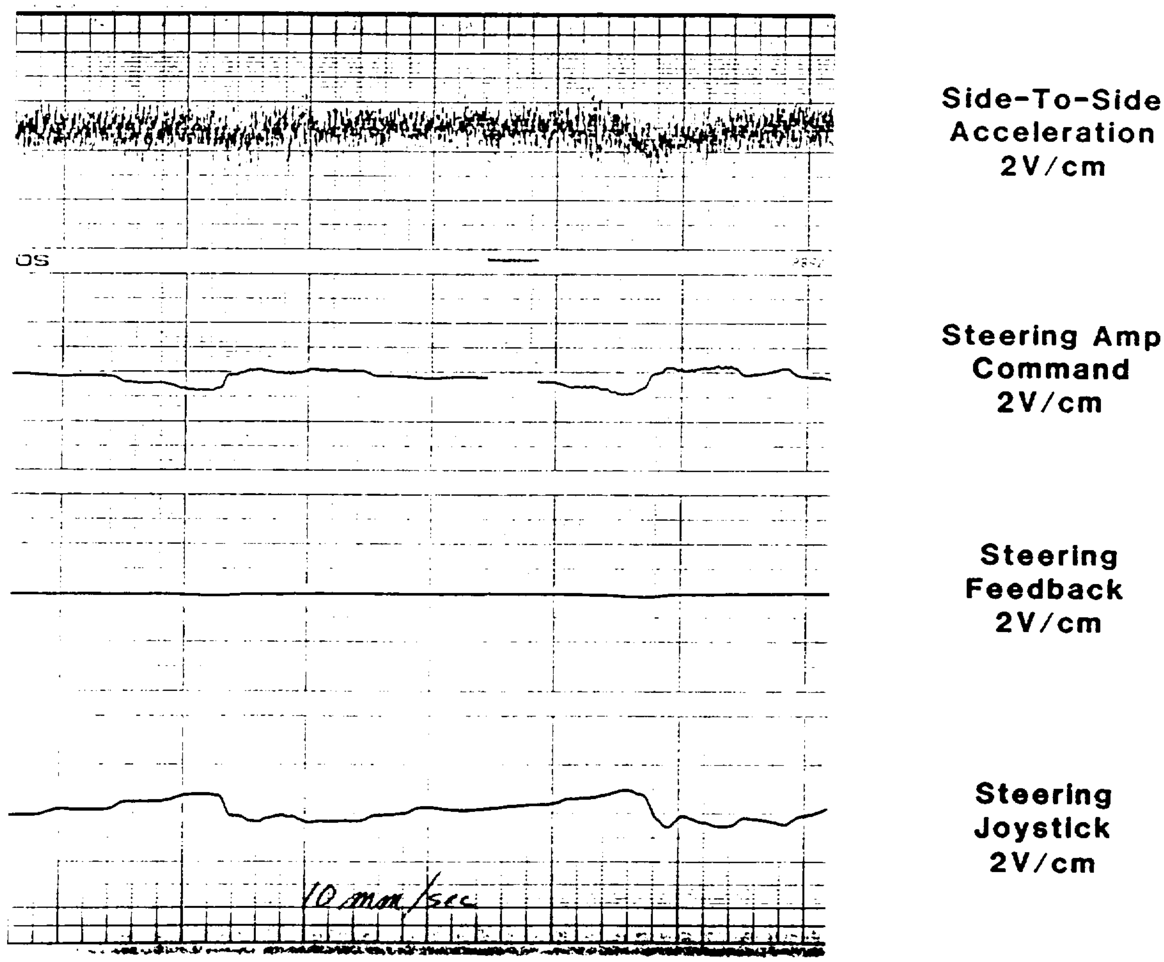


FIGURE C-69. TEST 3.2.1.4(C)

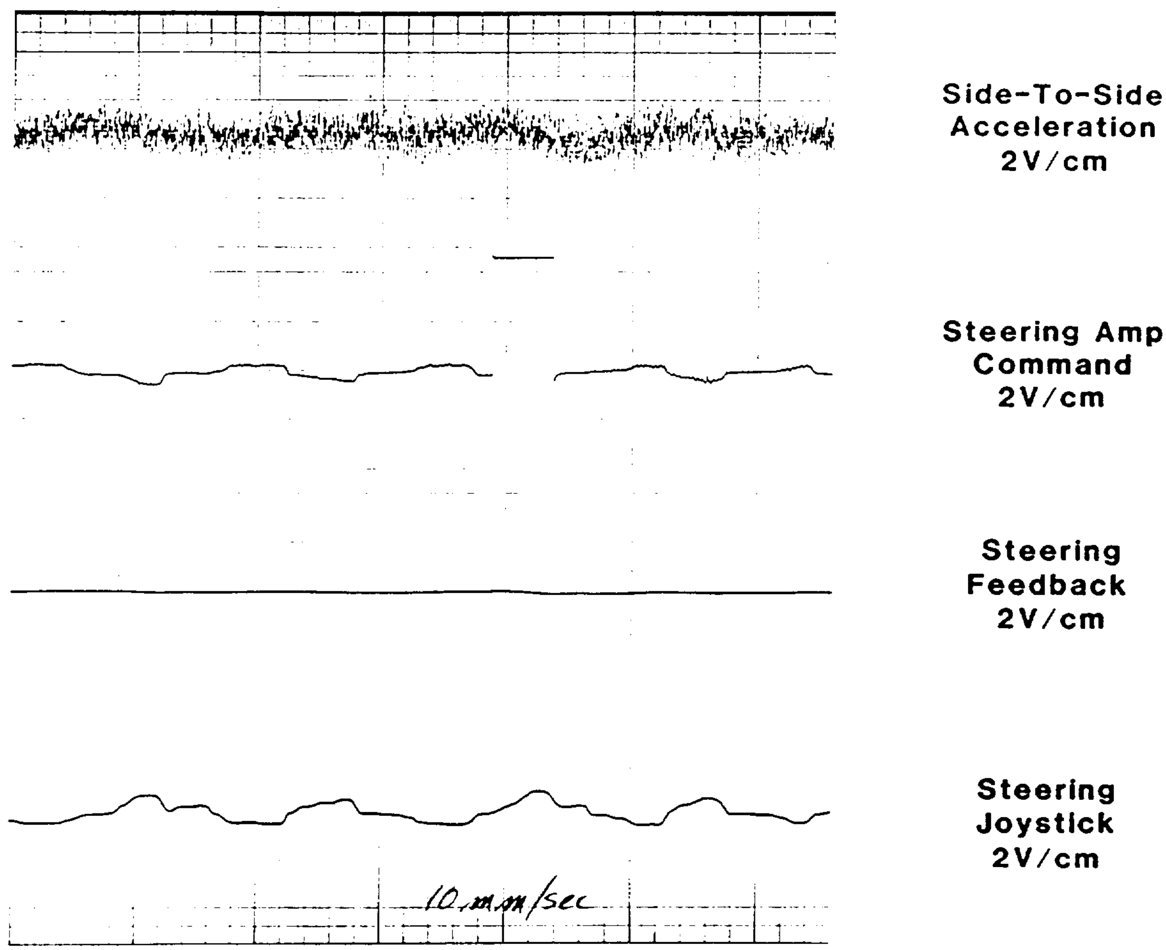
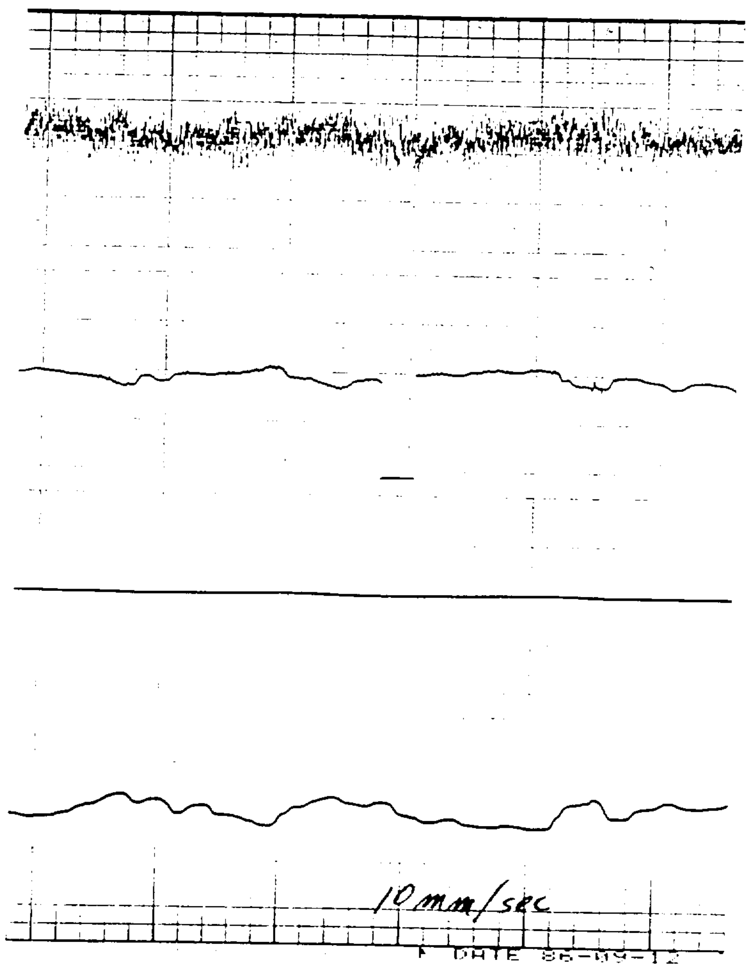


FIGURE C-70. TEST 3.2.1.4(D)



Side-To-Side Acceleration 2V/cm

Steering Amp Command 2V/cm

Steering Feedback 2V/cm

Steering Joystick 2V/cm

FIGURE C-71. TEST 3.2.1.4(E)

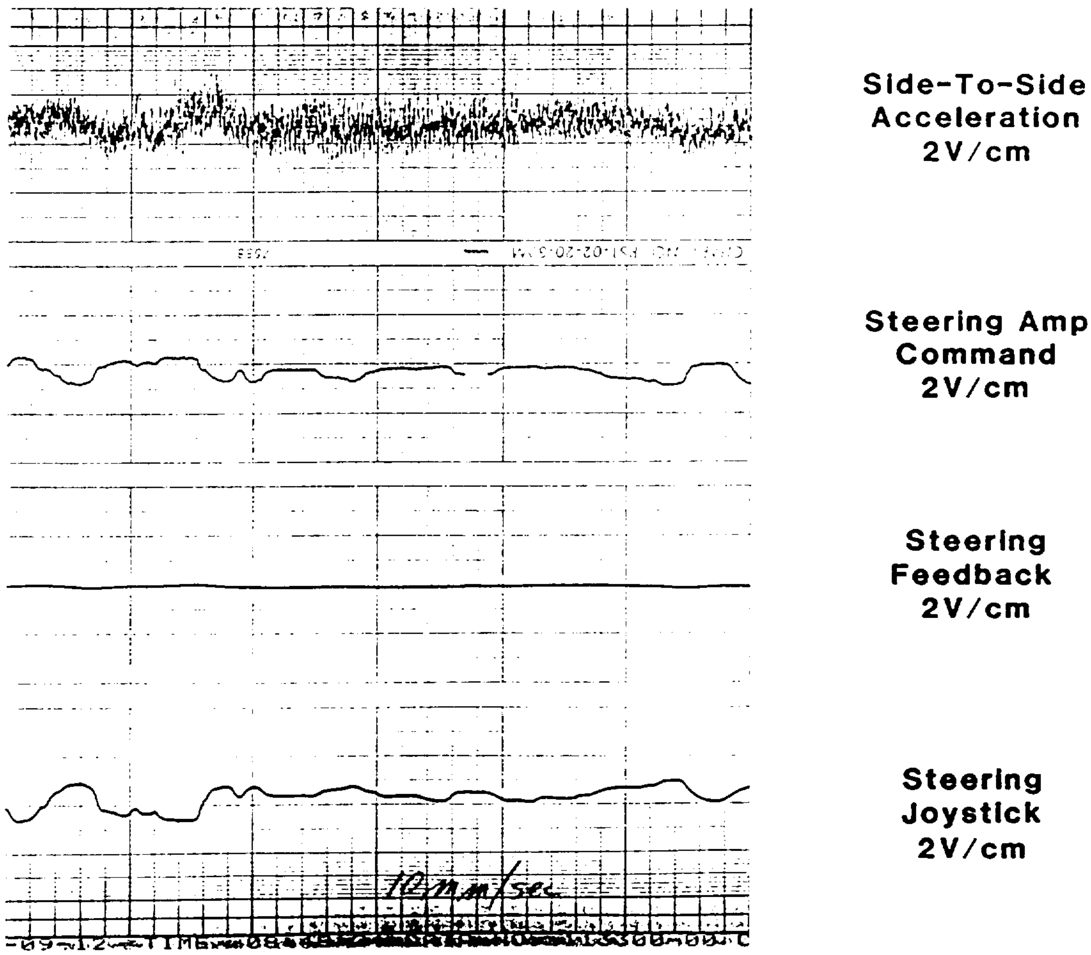


FIGURE C-72. TEST 3.2.1.4(F)

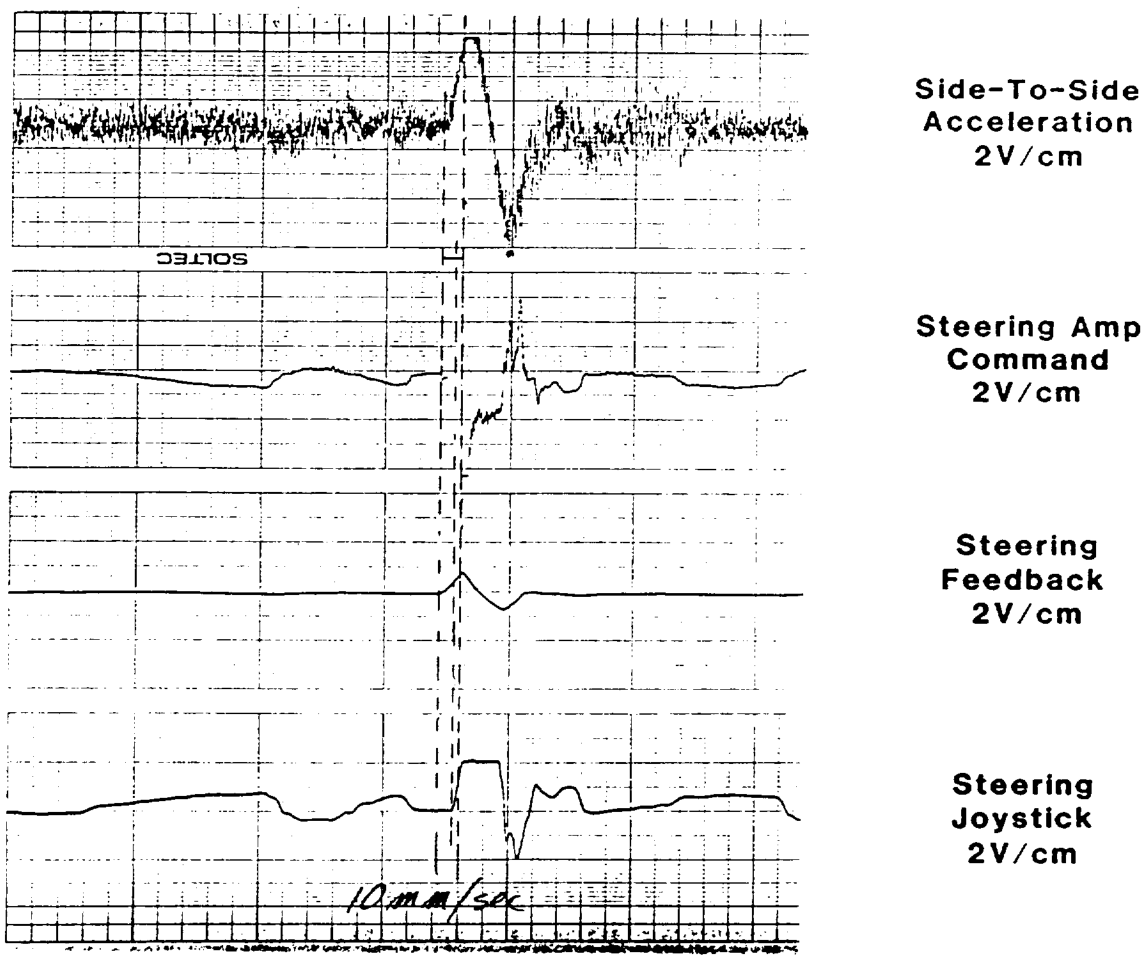


FIGURE C-73. TEST 3.2.1.5(A) INITIAL

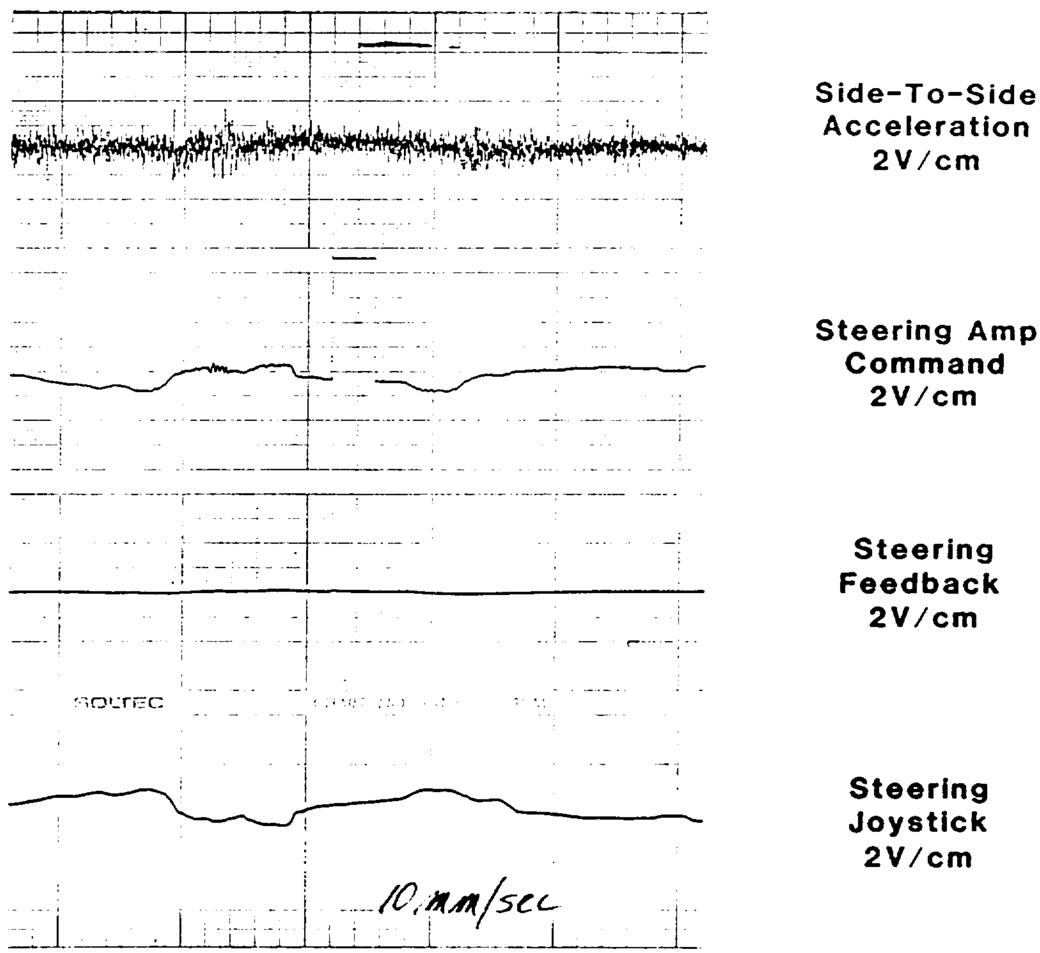


FIGURE C-74. TEST 3.2.1.5(A) RE-TEST

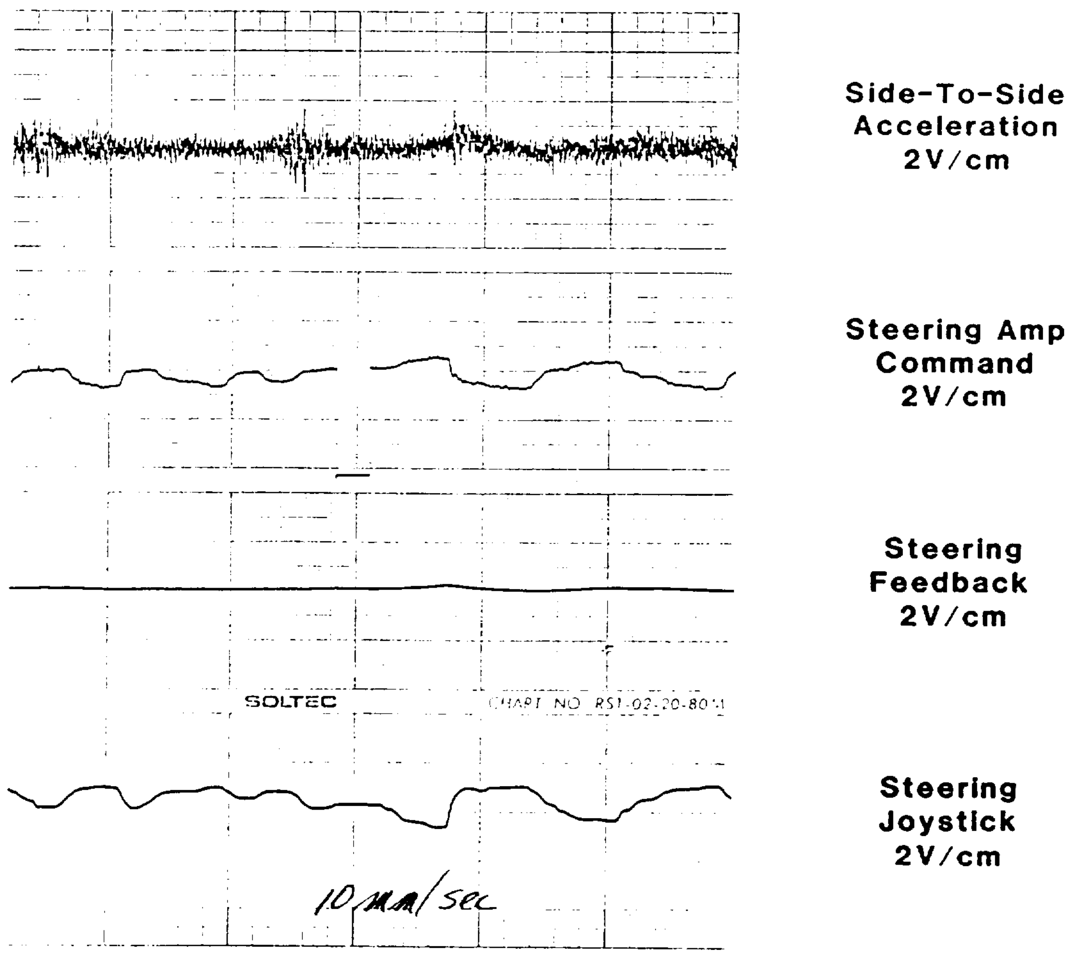
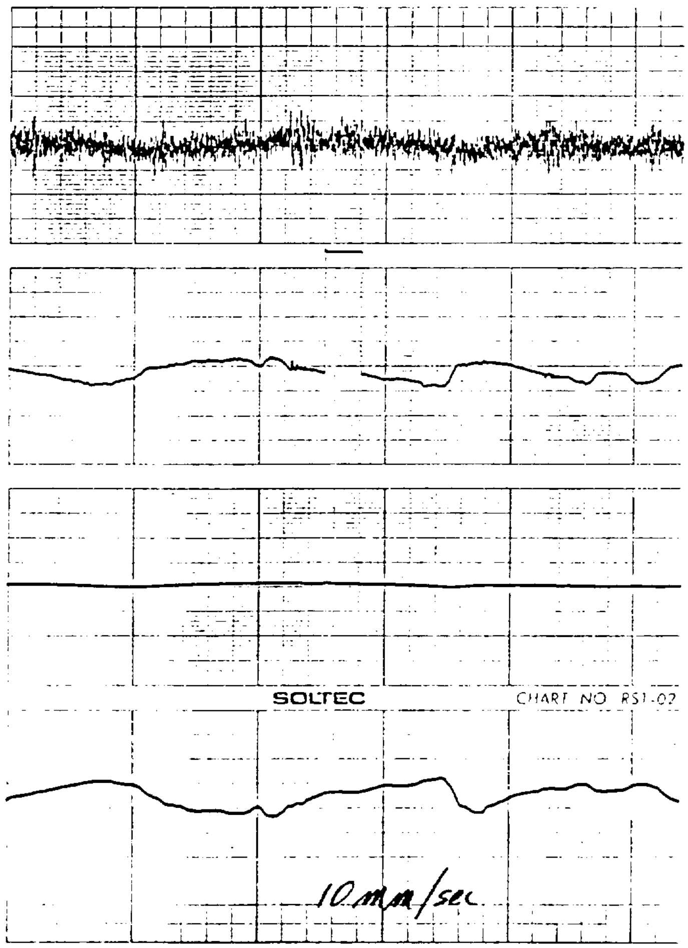


FIGURE C-75. TEST 3.2.1.5(B) RE-TEST



Side-To-Side Acceleration 2V/cm

Steering Amp Command 2V/cm

Steering Feedback 2V/cm

Steering Joystick 2V/cm

FIGURE C-76. TEST 3.2.1.5(C) RE-TEST

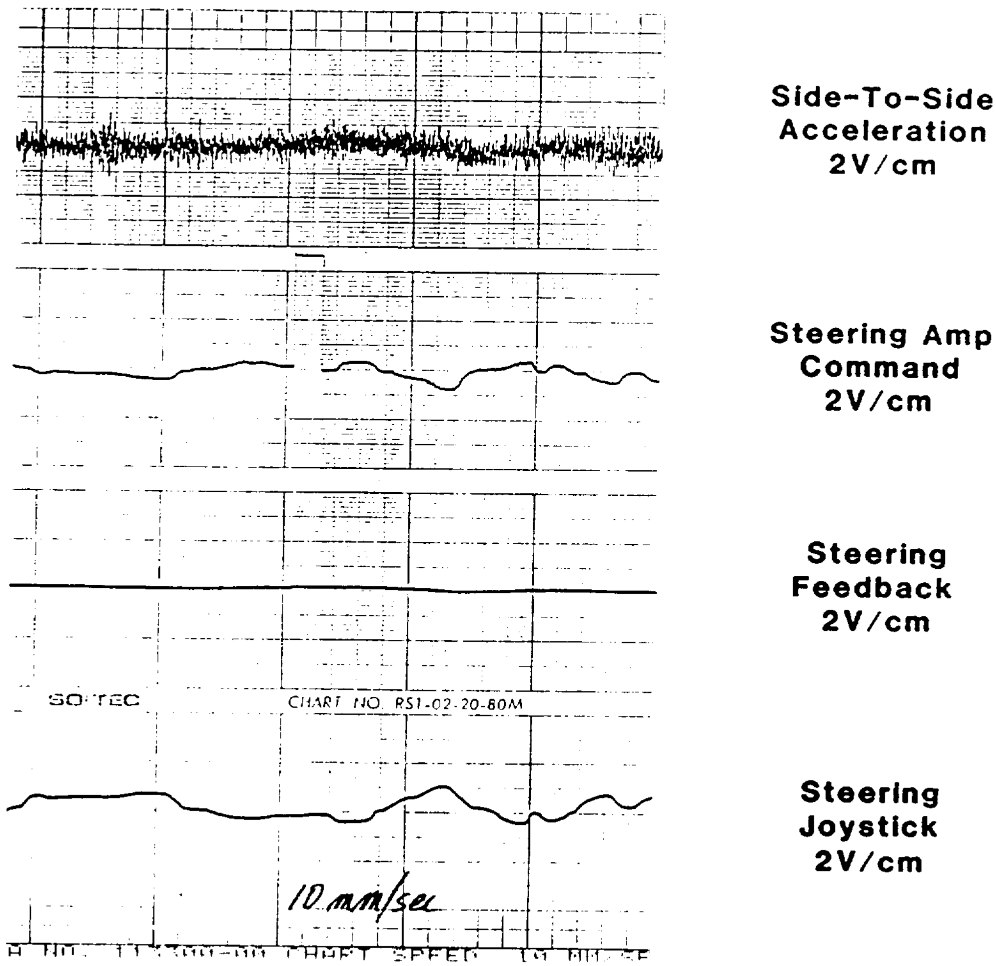


FIGURE C-77. TEST 3.2.1.5(D) RE-TEST

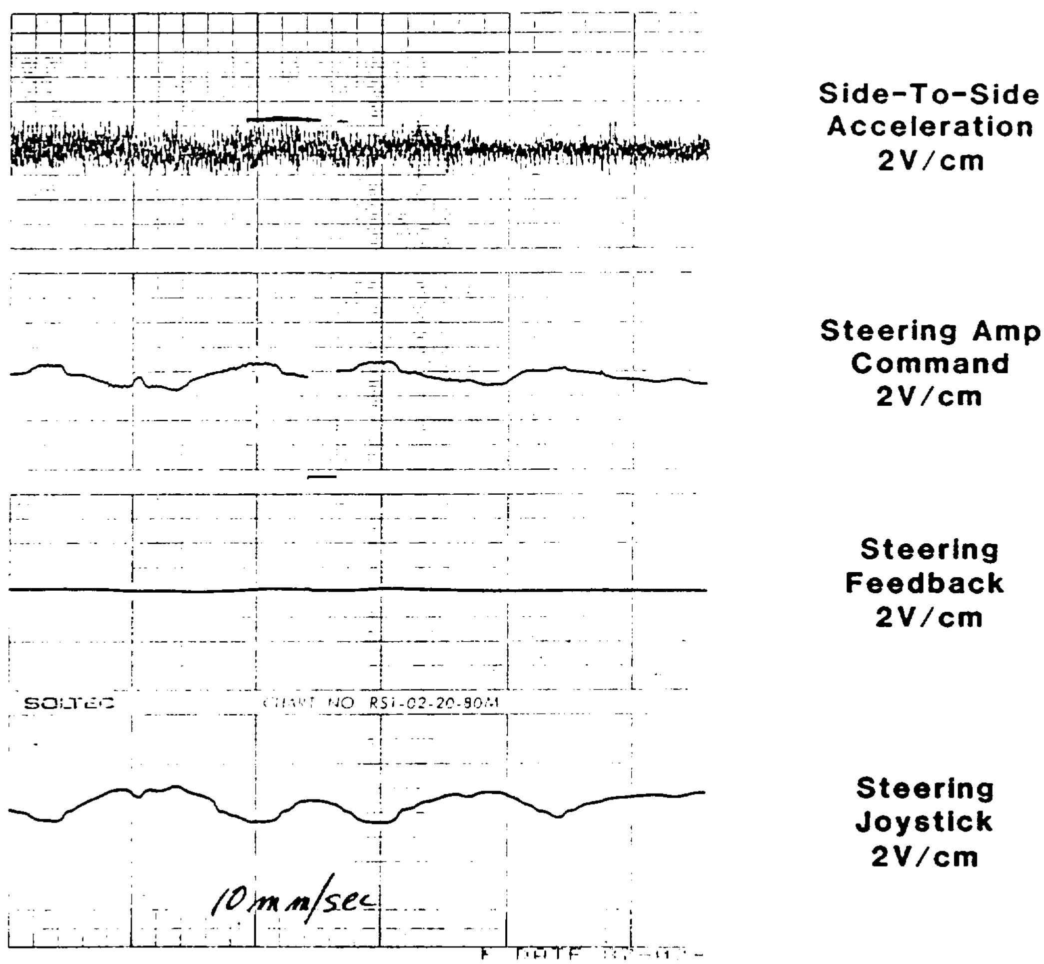


FIGURE C-78. TEST 3.2.1.5(E) RE-TEST

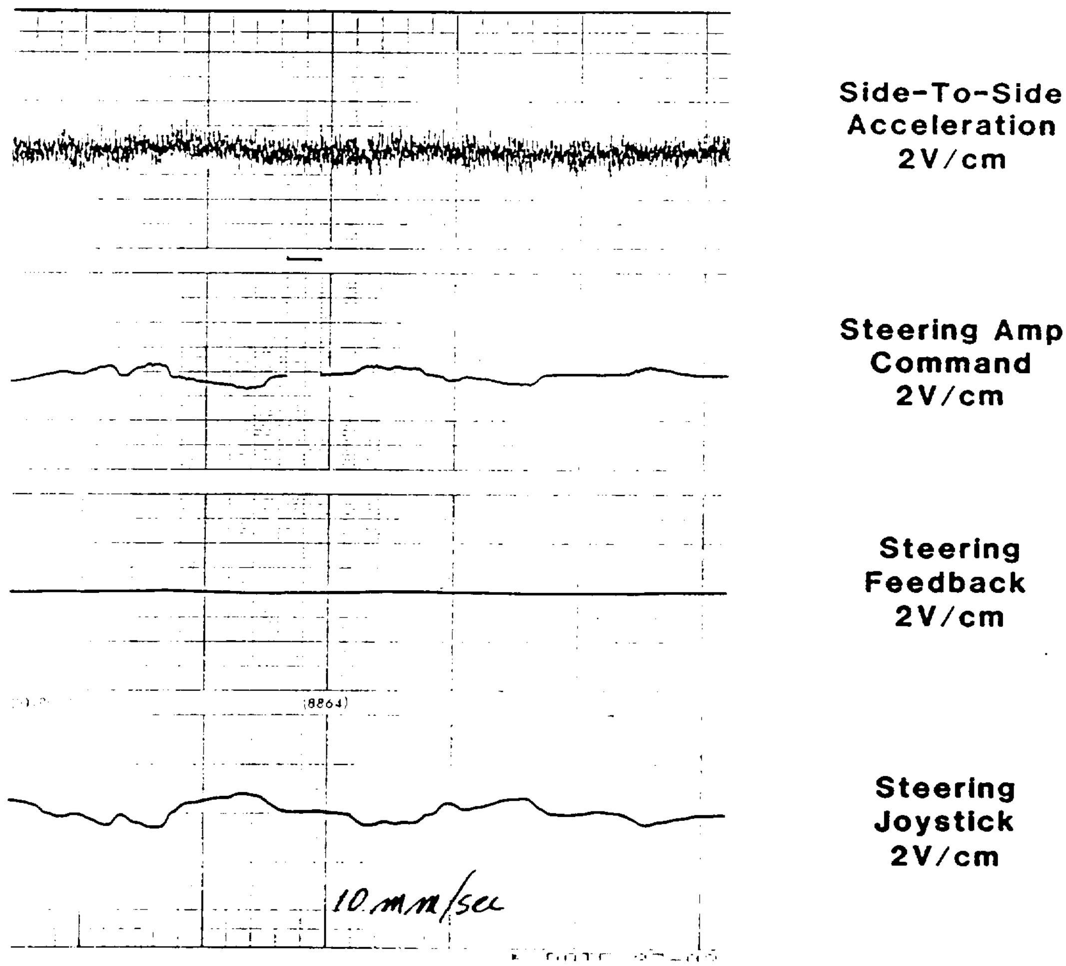


FIGURE C-79. TEST 3.2.1.5(F) RE-TEST

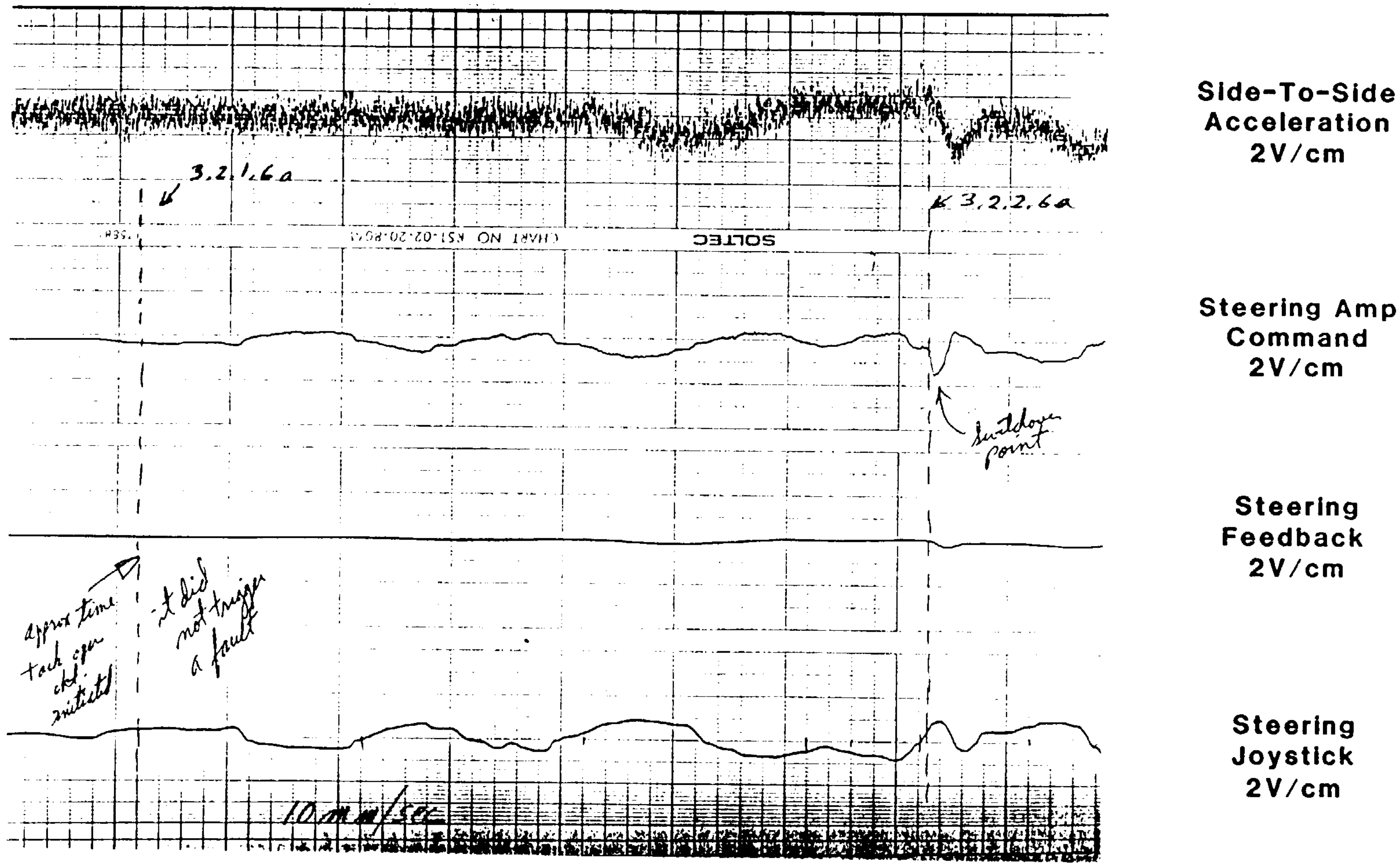


FIGURE C-80. TESTS 3.2.1.6(a) AND 3.2.2.6(a)

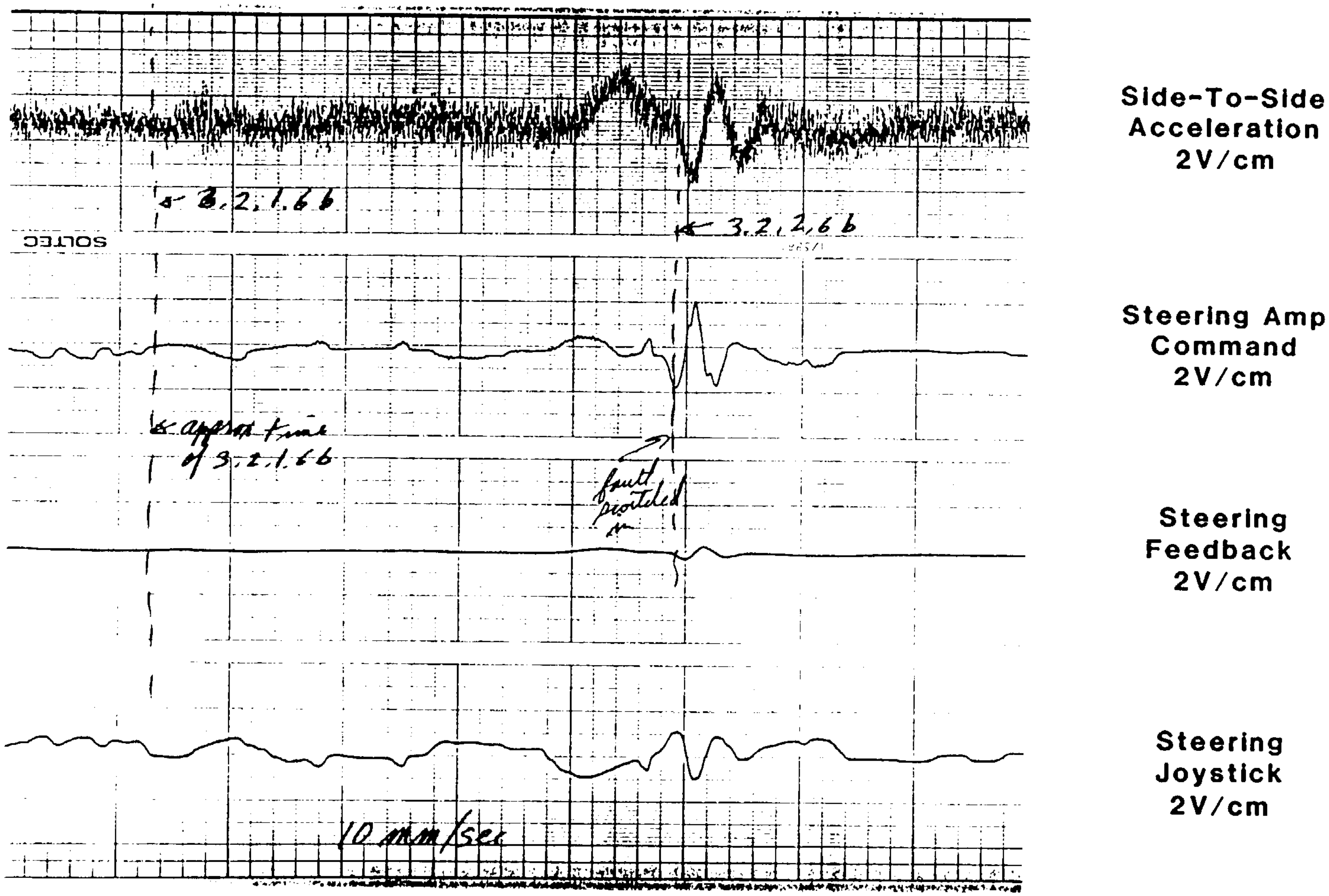


FIGURE C-81. TESTS 3.2.1.6(b) AND 3.2.2.6(b)

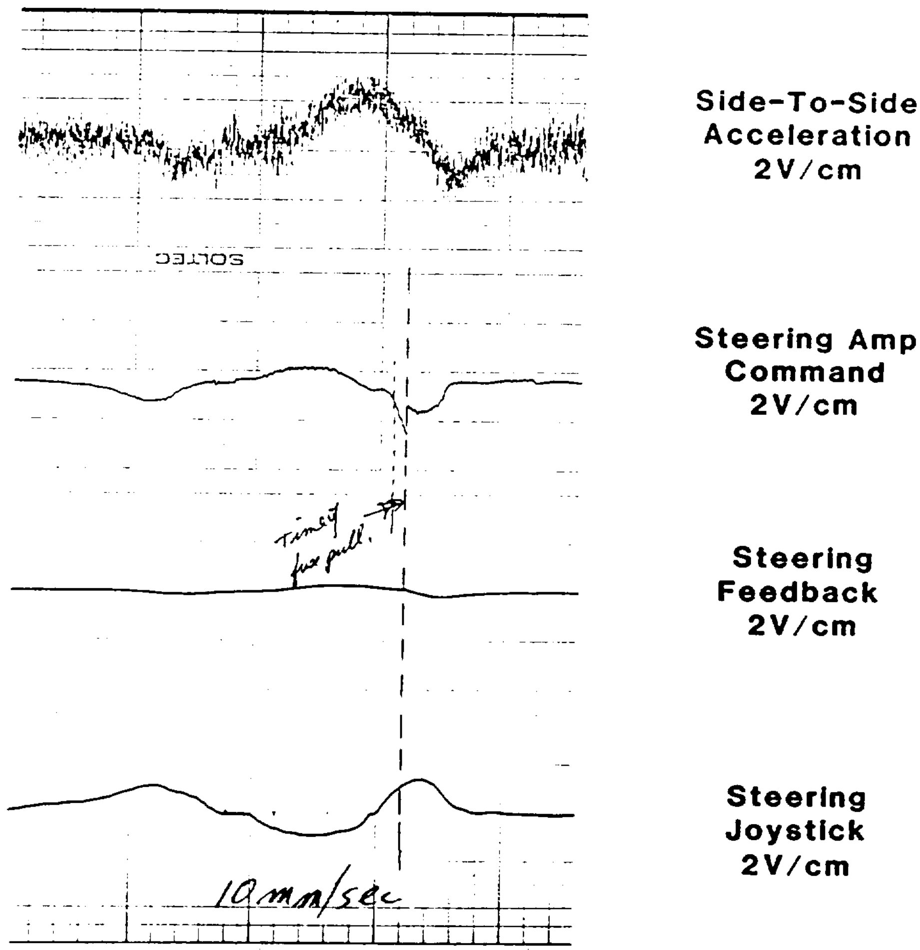


FIGURE C-82. TEST 3.2.2.1(a)

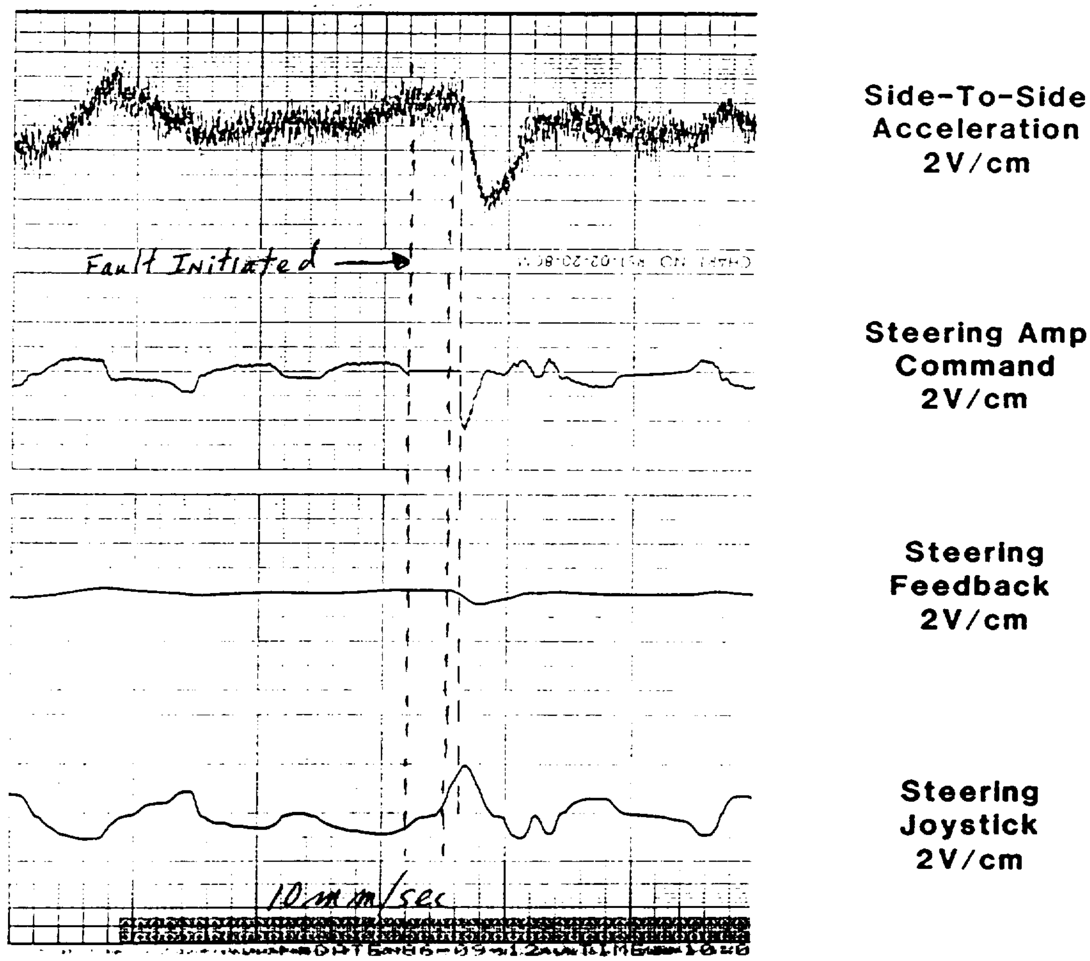


FIGURE C-84. TEST 3.2.2.2(a)

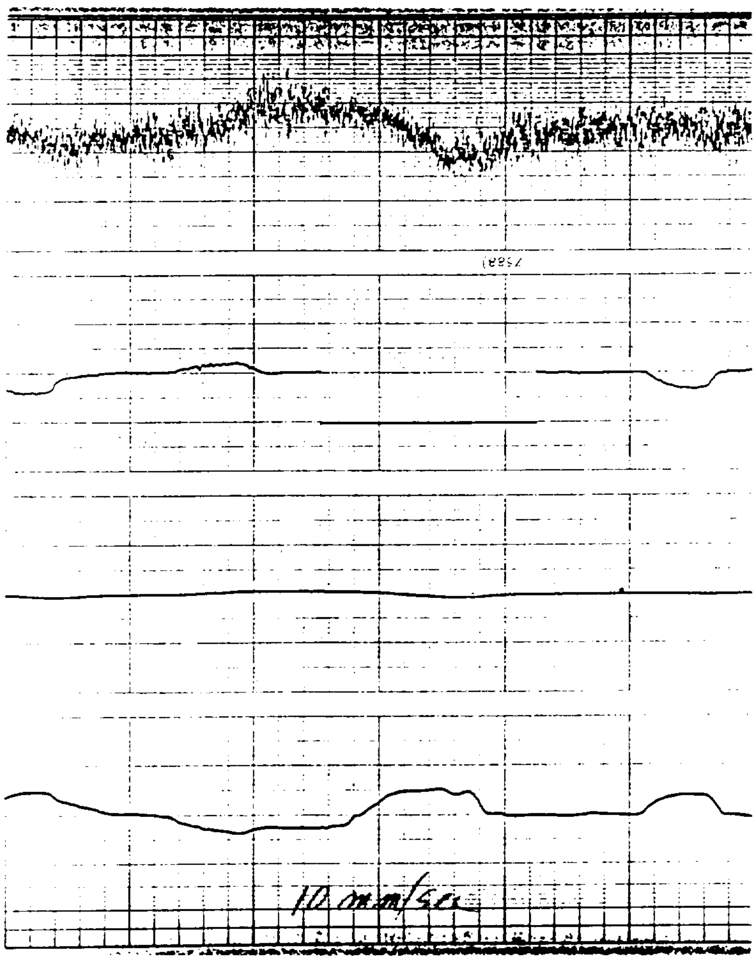
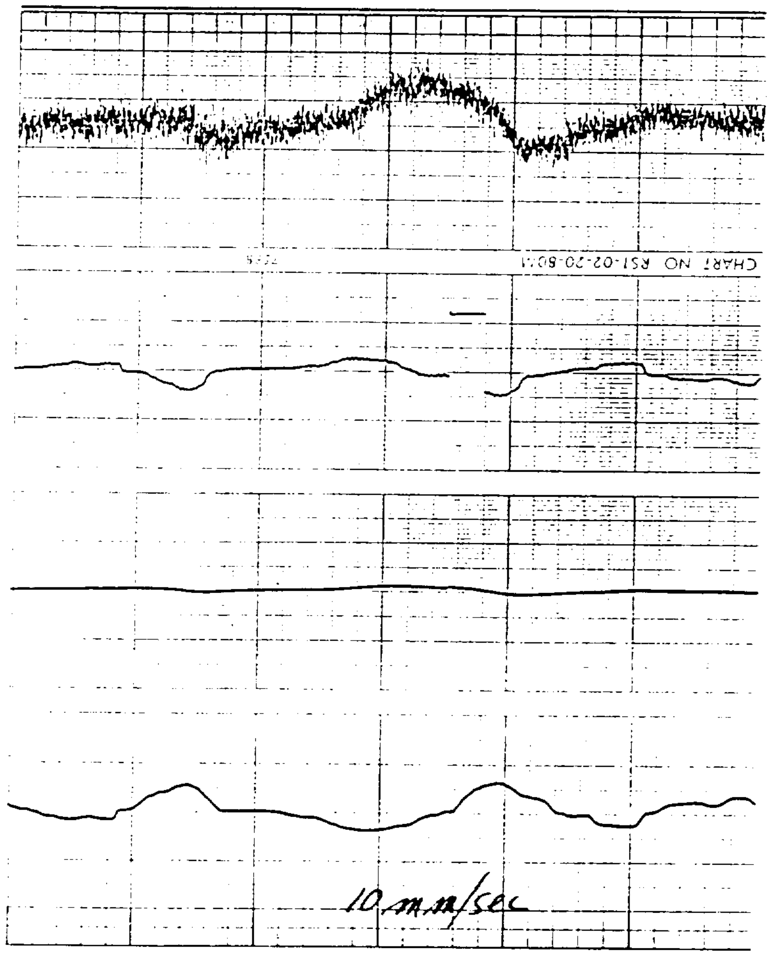


FIGURE C-85. TEST 3.2.2.2(b)



Side-To-Side Acceleration 2V/cm

Steering Amp Command 2V/cm

Steering Feedback 2V/cm

Steering Joystick 2V/cm

FIGURE C-86. TEST 3.2.2.2(c)

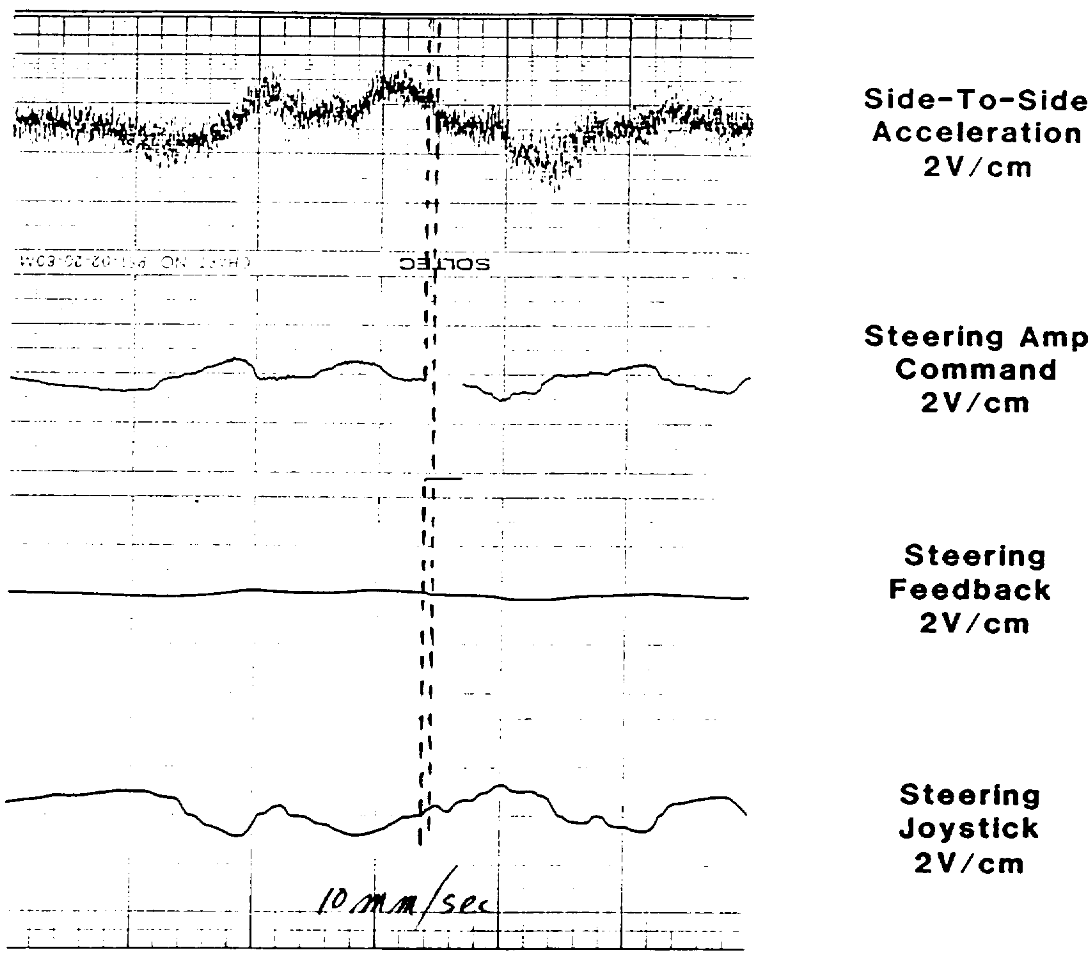


FIGURE C-87. TEST 3.2.2.2(d)

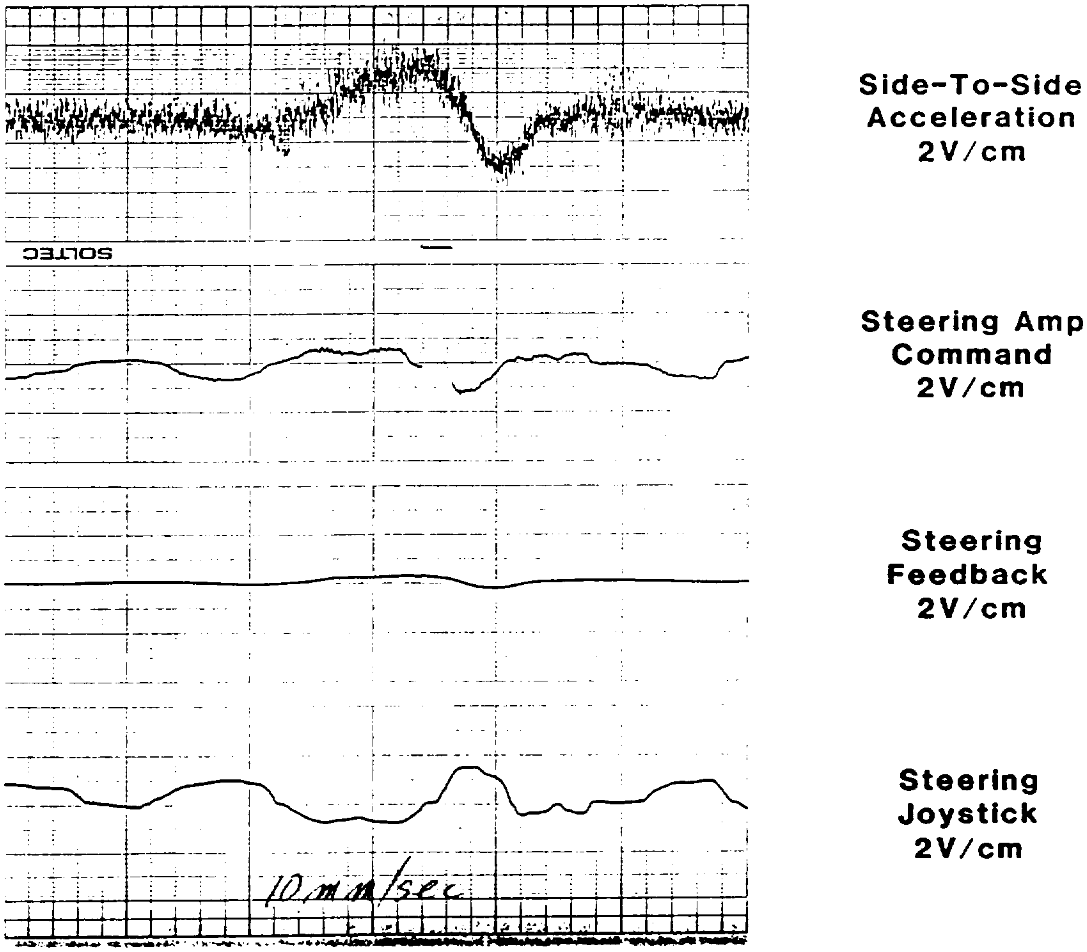


FIGURE C-88. TEST 3.2.2.2(e)

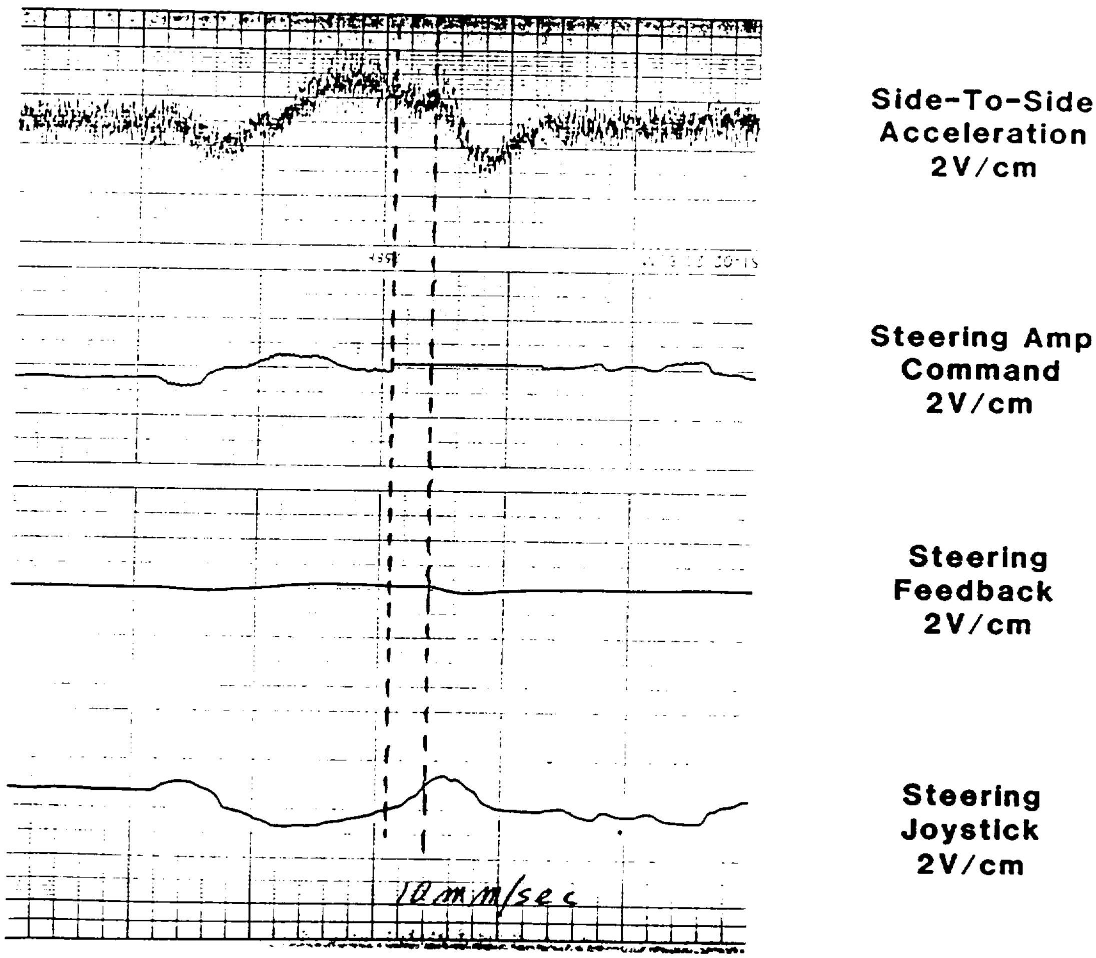


FIGURE C-89. TEST 3.2.2.2(f)

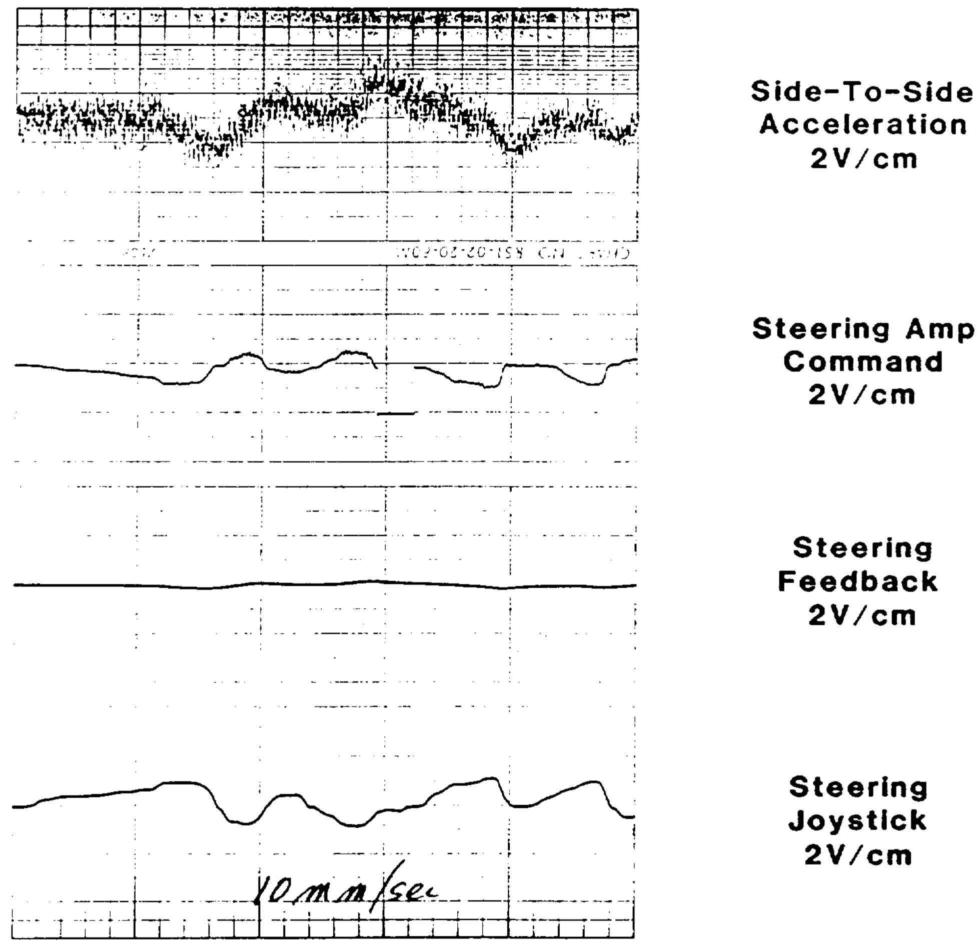


FIGURE C-90. TEST 3.2.2.2(g)

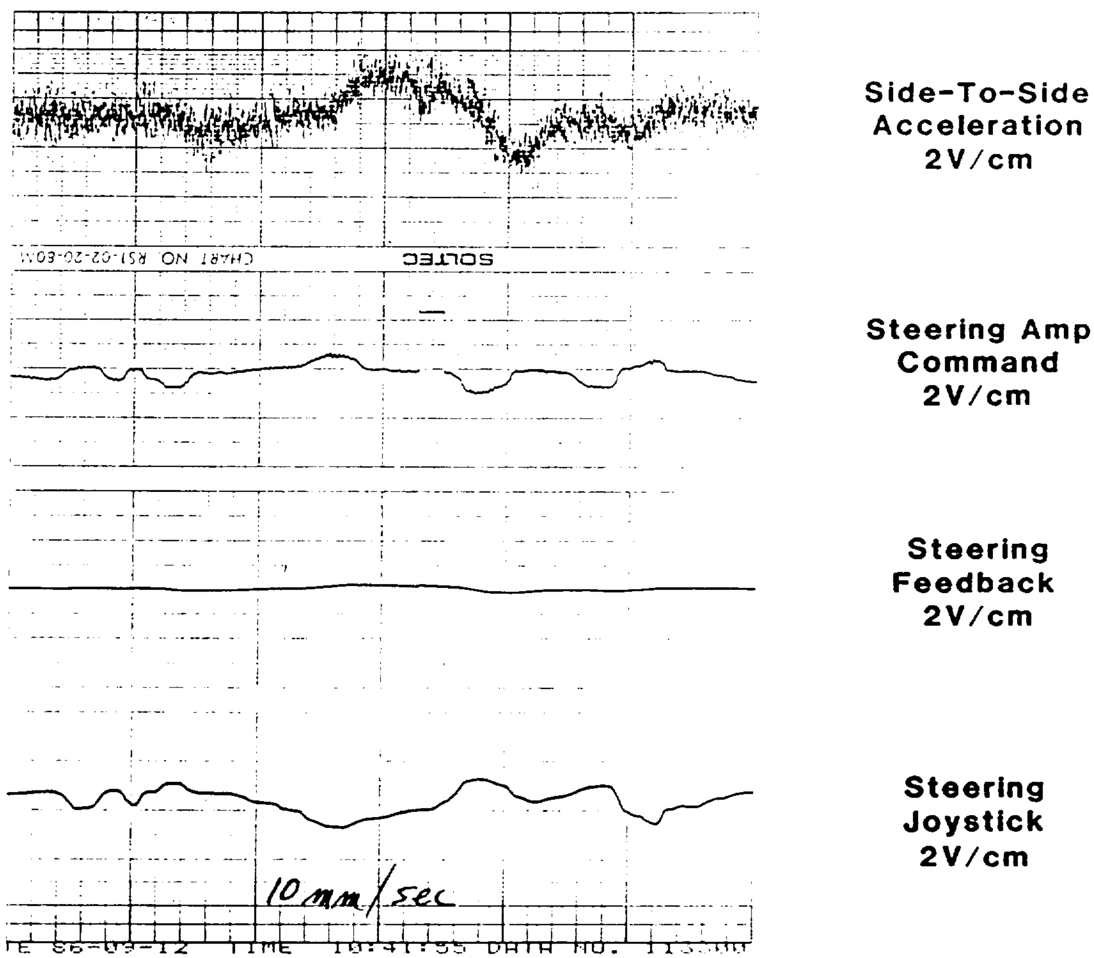


FIGURE C-91. TEST 3.2.2.2(h)

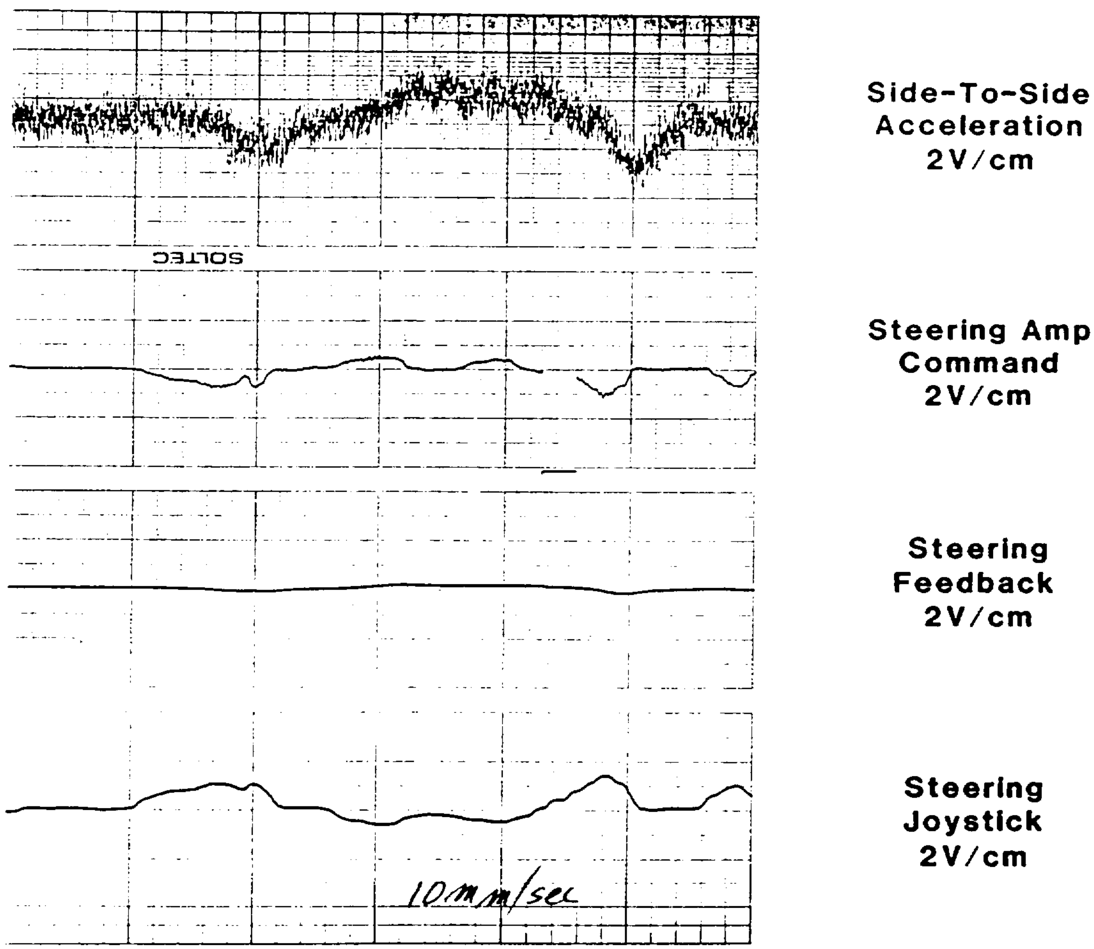


FIGURE C-92. TEST 3.2.2.2(i)

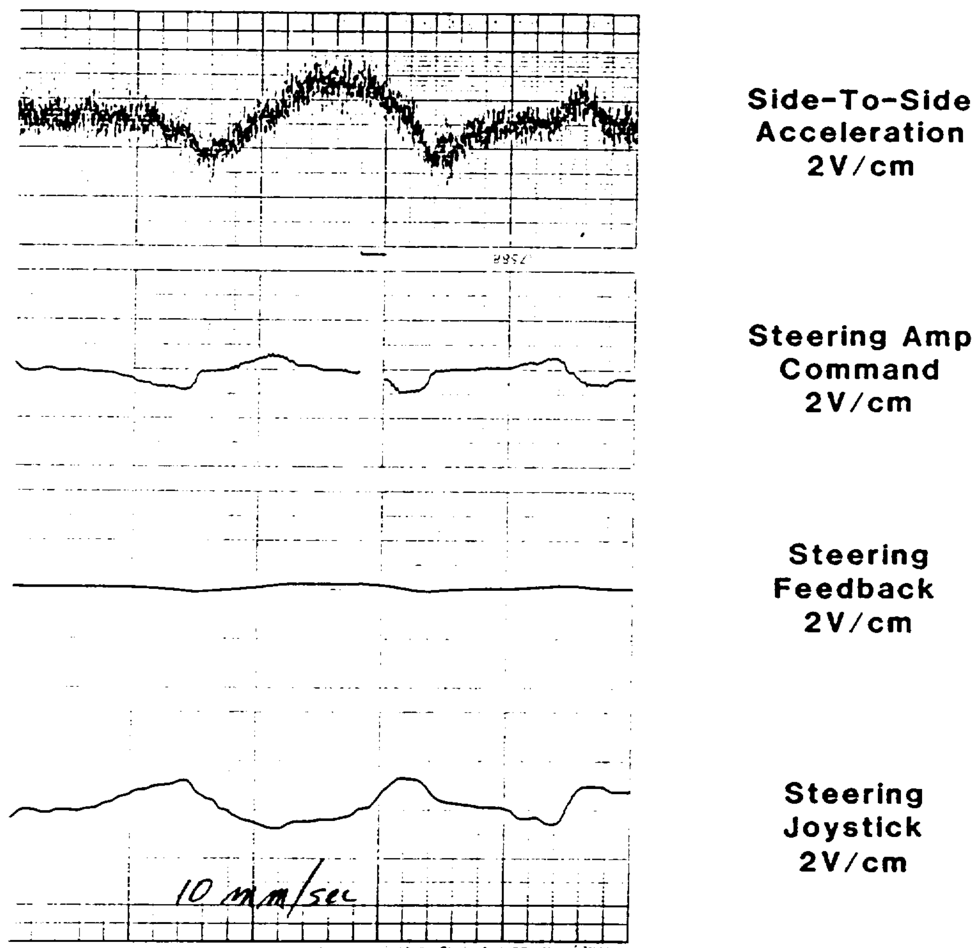


FIGURE C-93. TEST 3.2.2.2(j)

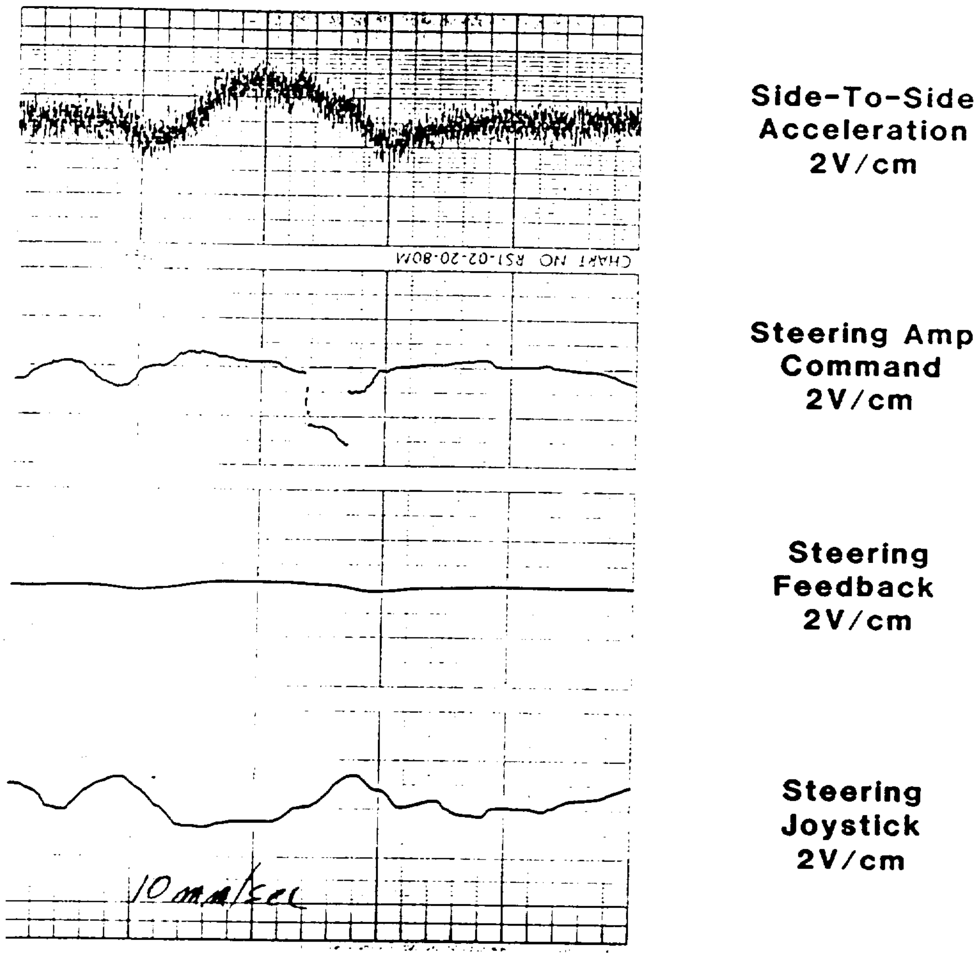


FIGURE C-94. TEST 3.2.2.3(a)

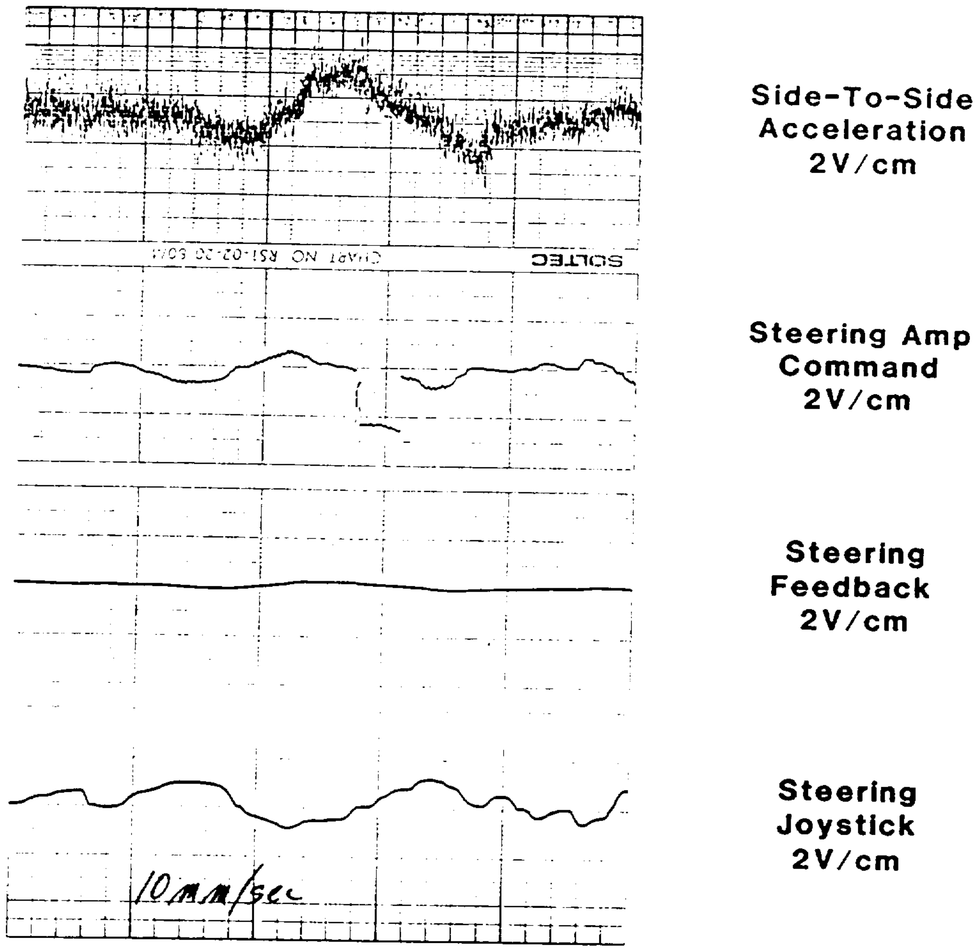


FIGURE C-95. TEST 3.2.2.3(b)

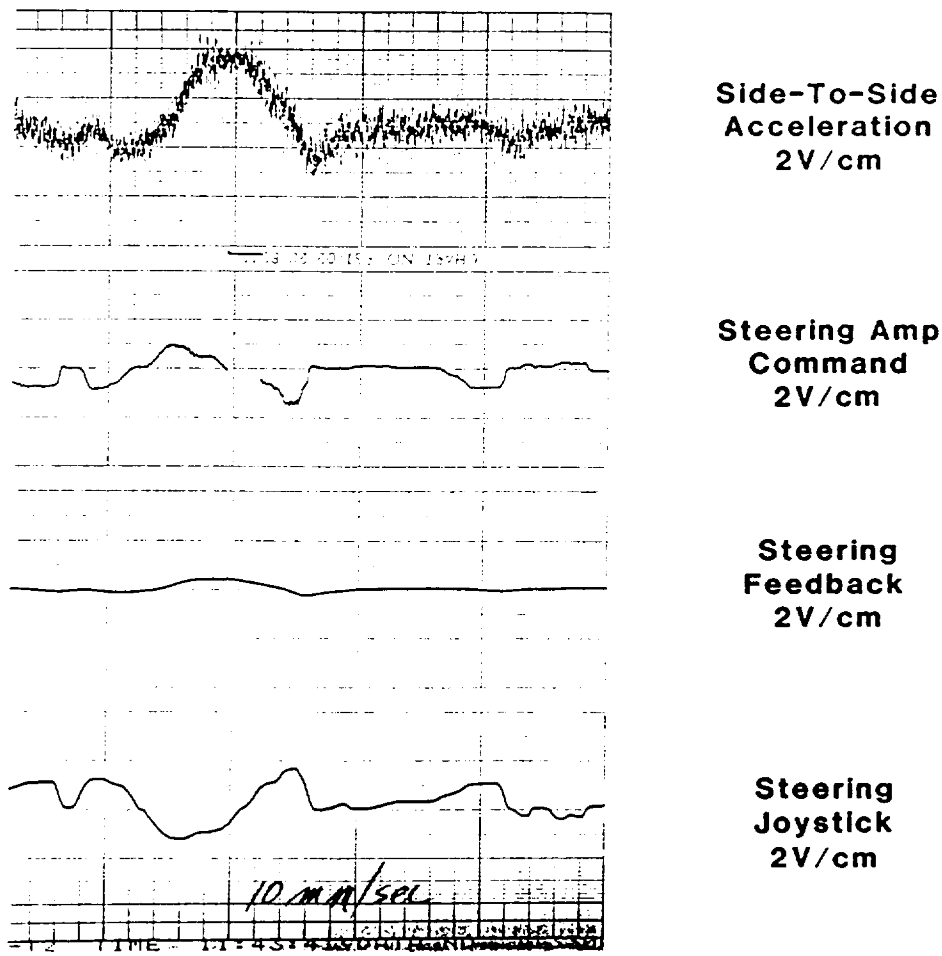


FIGURE C-96. TEST 3.2.2.4(a)

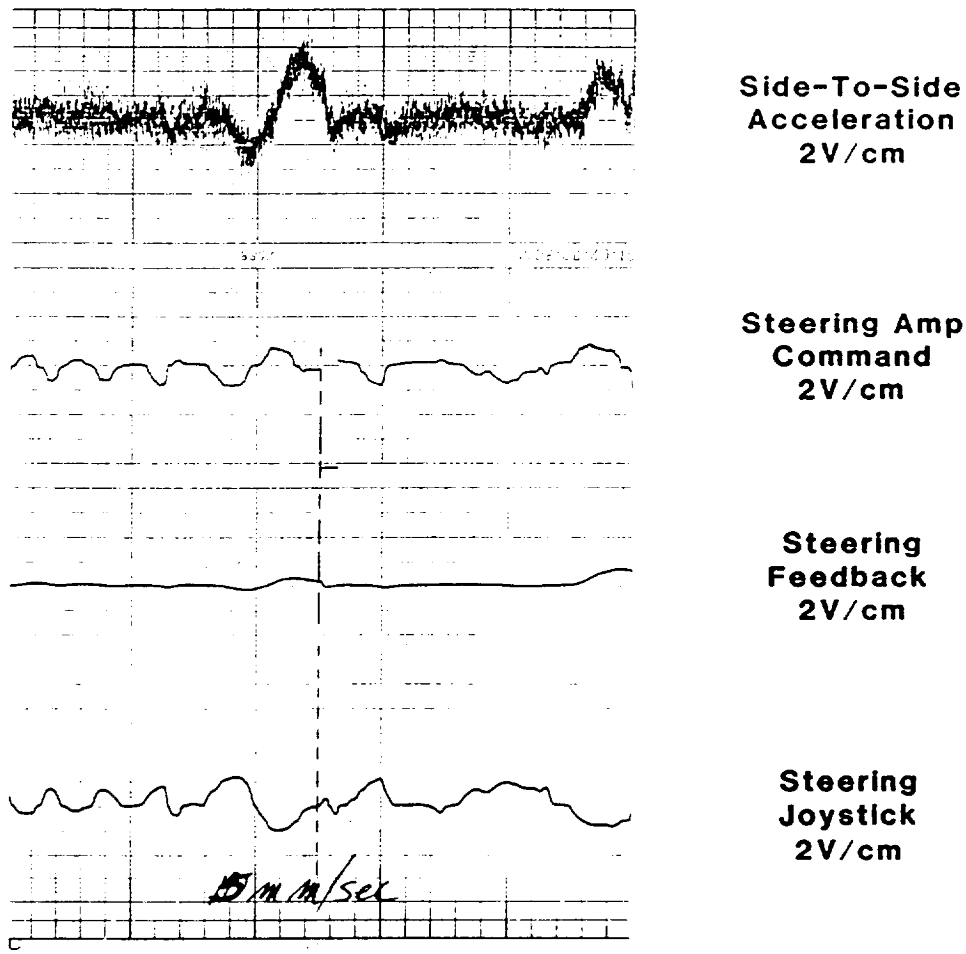


FIGURE C-97. TEST 3.2.2.4(b)

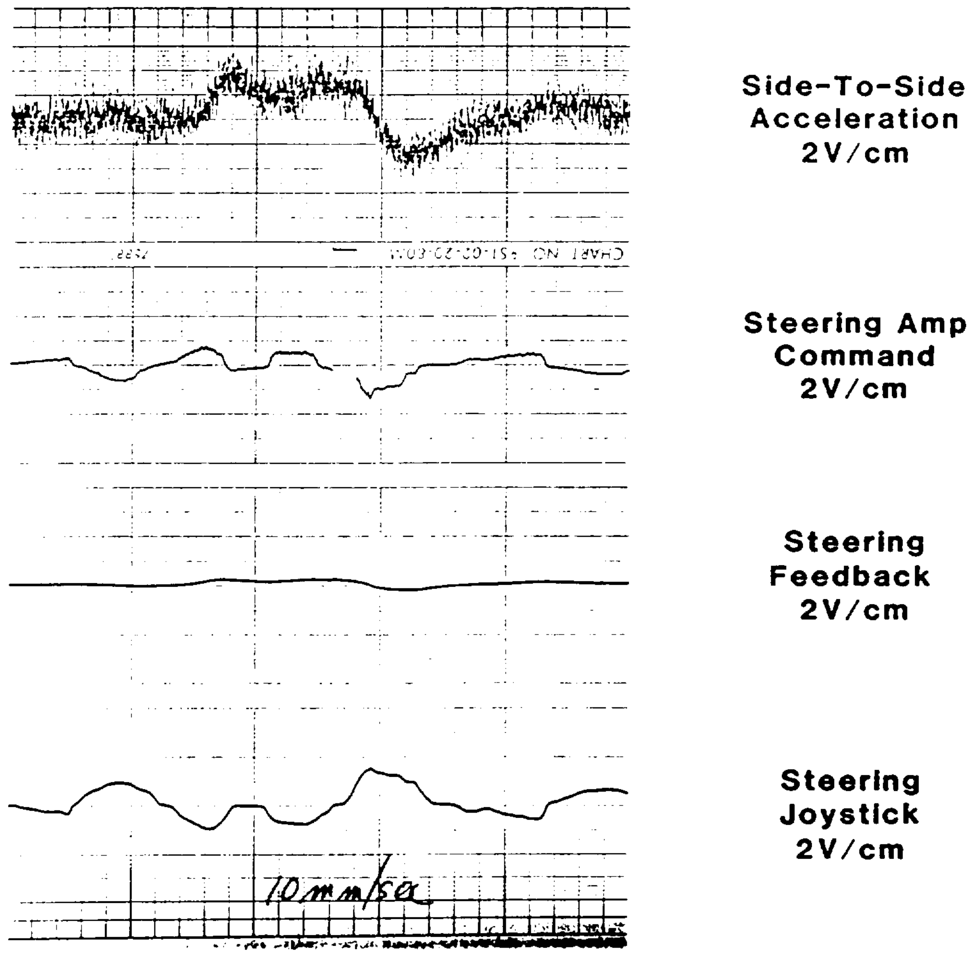


FIGURE C-98. TEST 3.2.2.4(c)

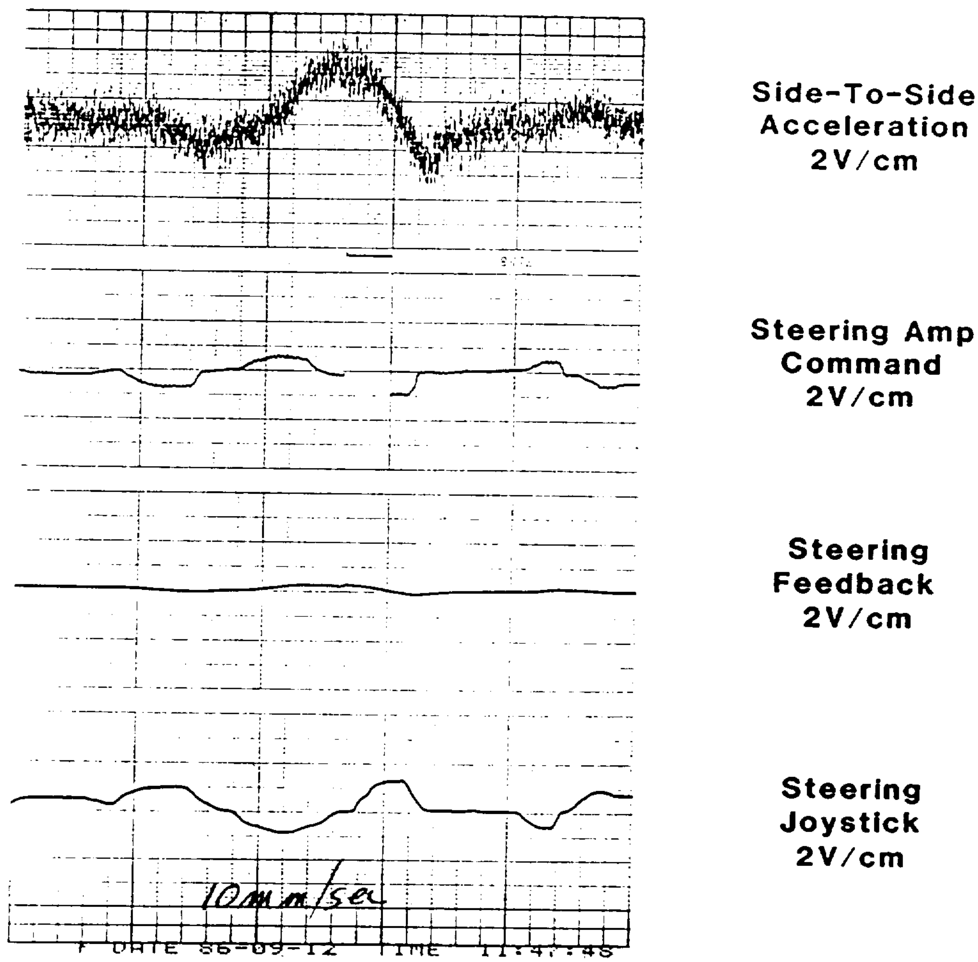


FIGURE C-99. TEST 3.2.2.4(d)

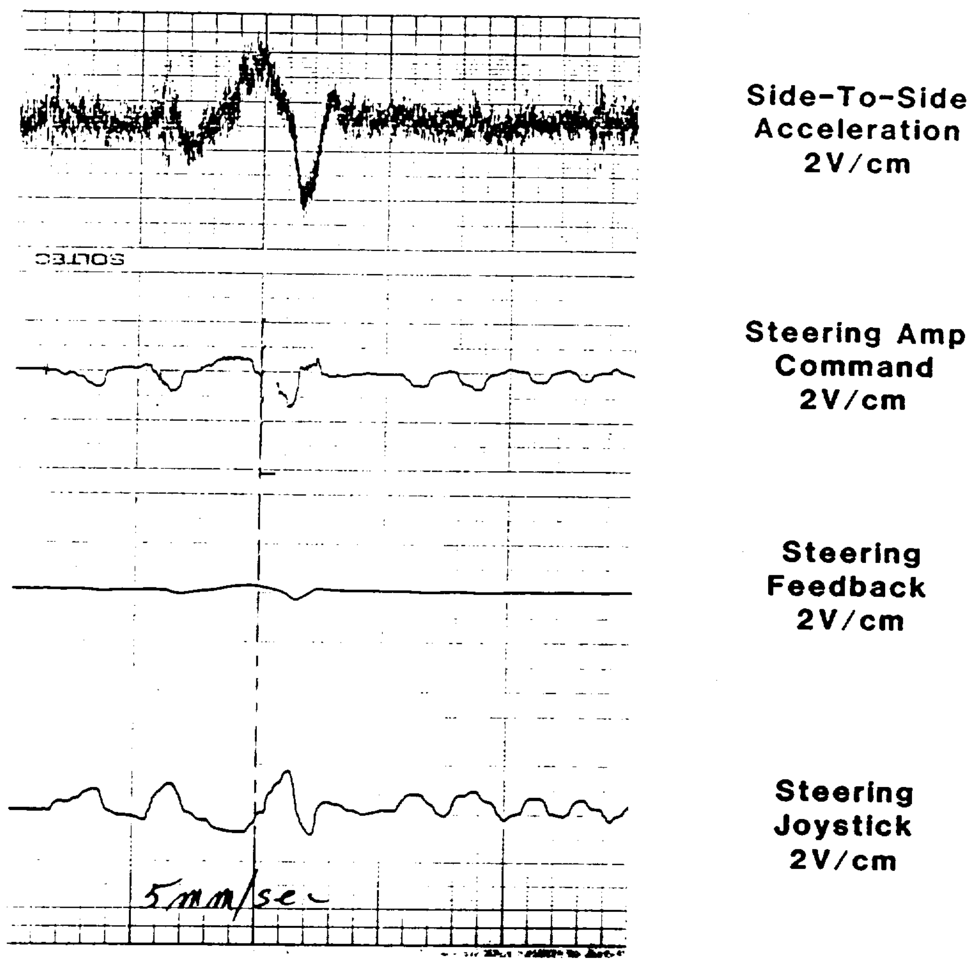


FIGURE C-100. TEST 3.2.2.4(e)

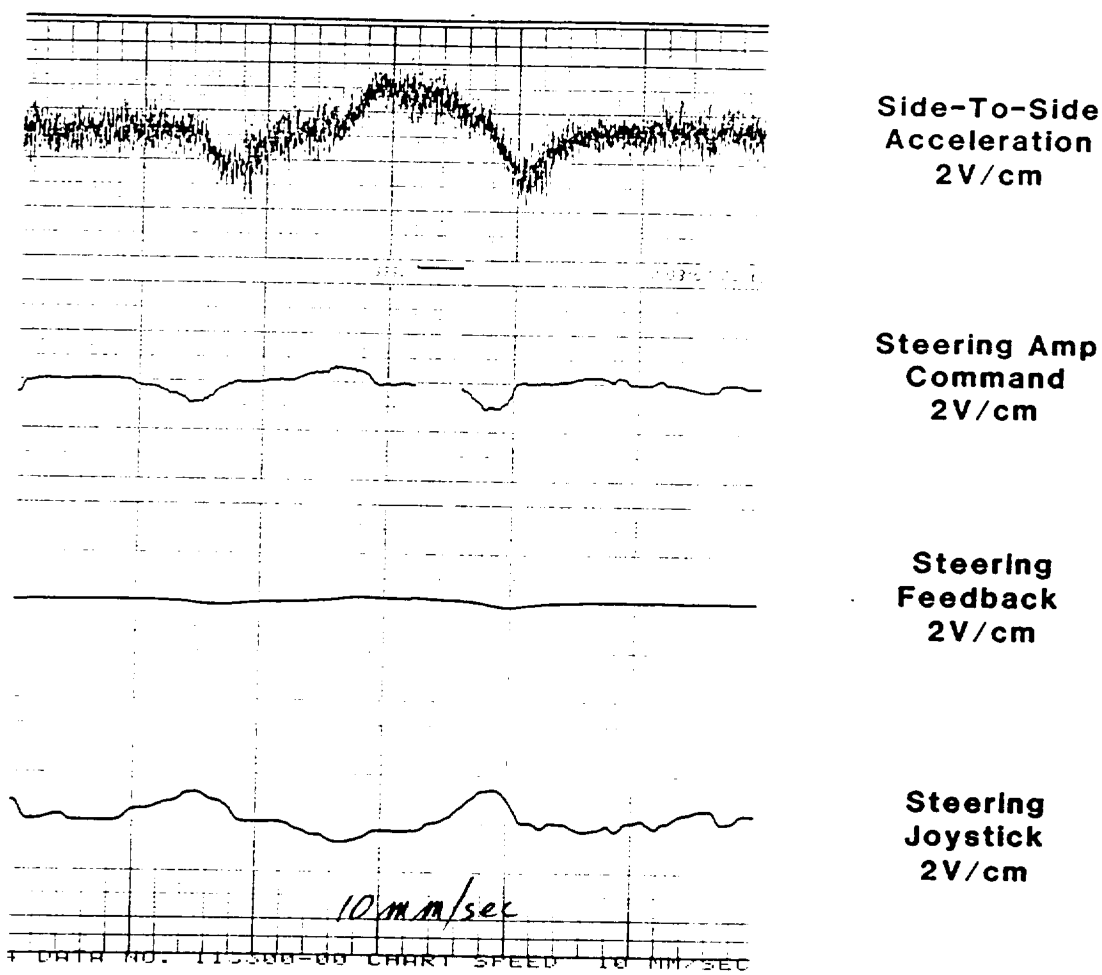


FIGURE C-101. TEST 3.2.2.4(f)

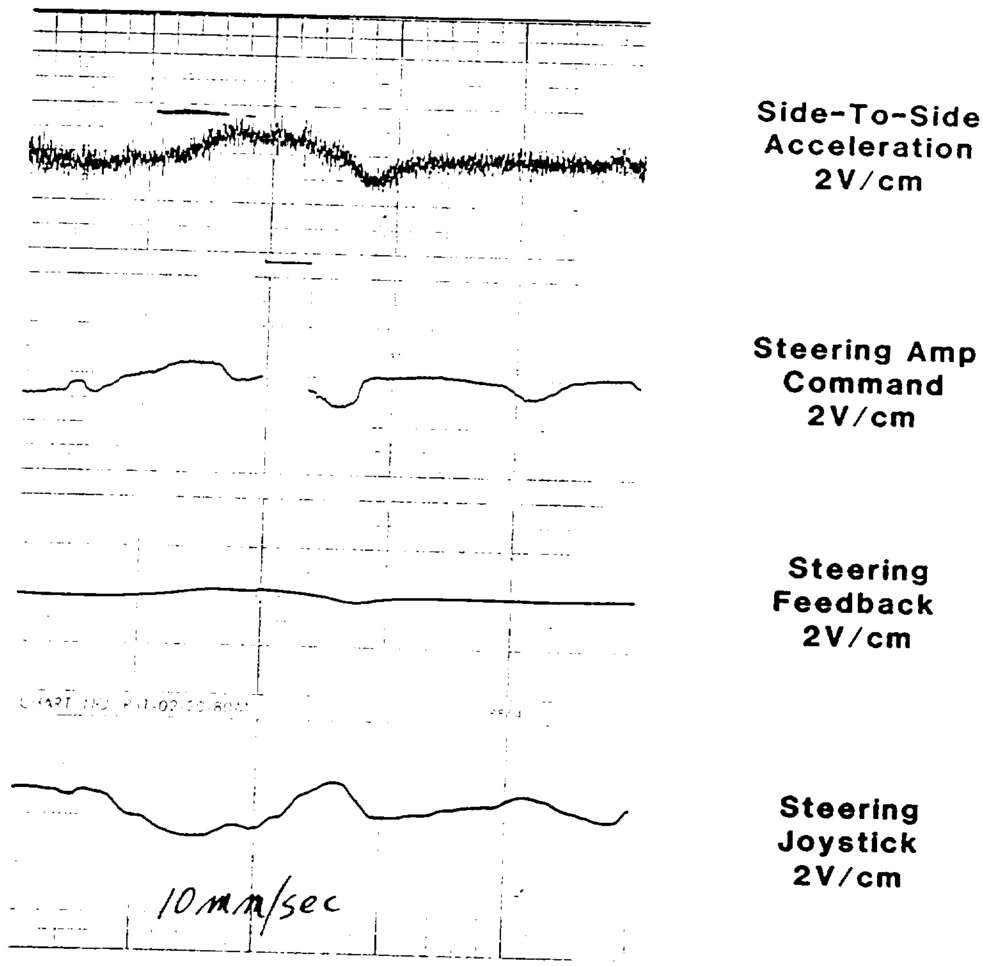


FIGURE C-102. TEST 3.2.2.5(a) RE-TEST

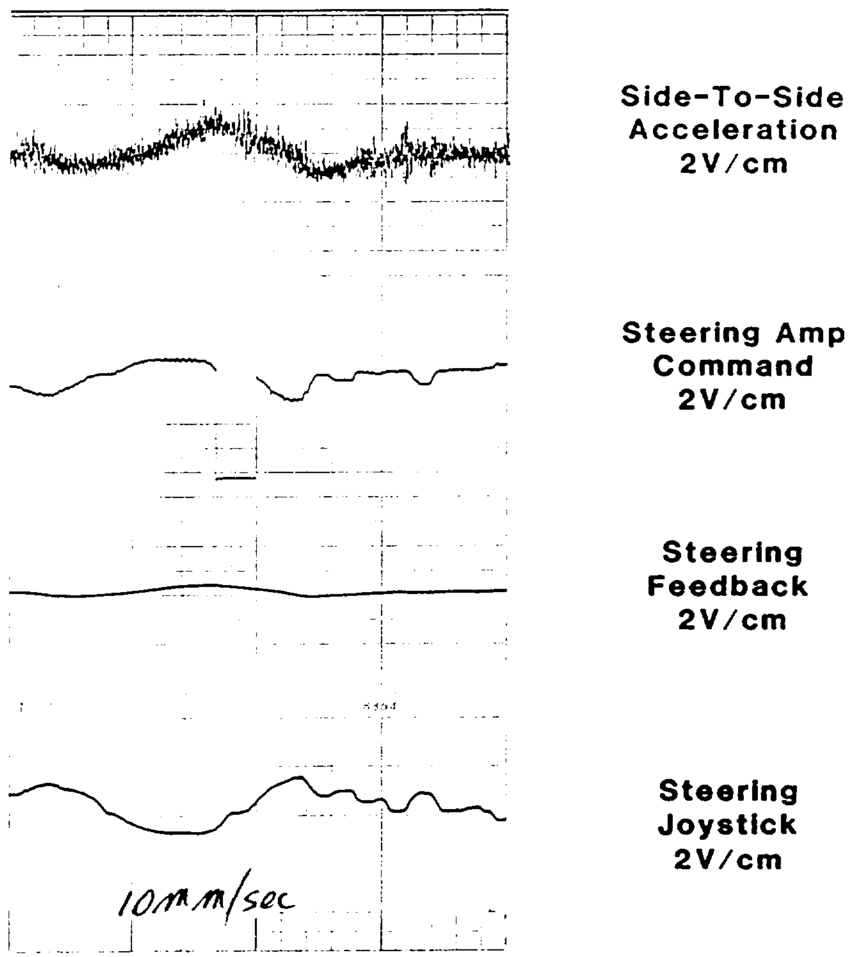


FIGURE C-103. TEST 3.2.2.5(b) RE-TEST

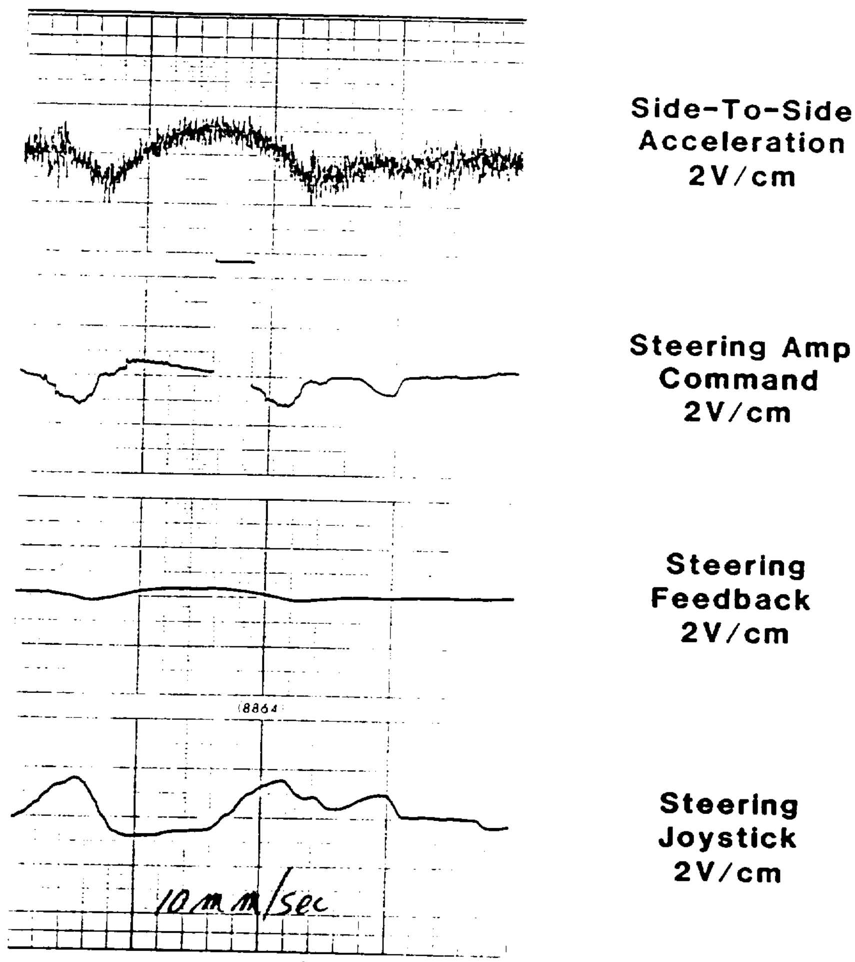


FIGURE C-104. TEST 3.2.2.5(c) RE-TEST

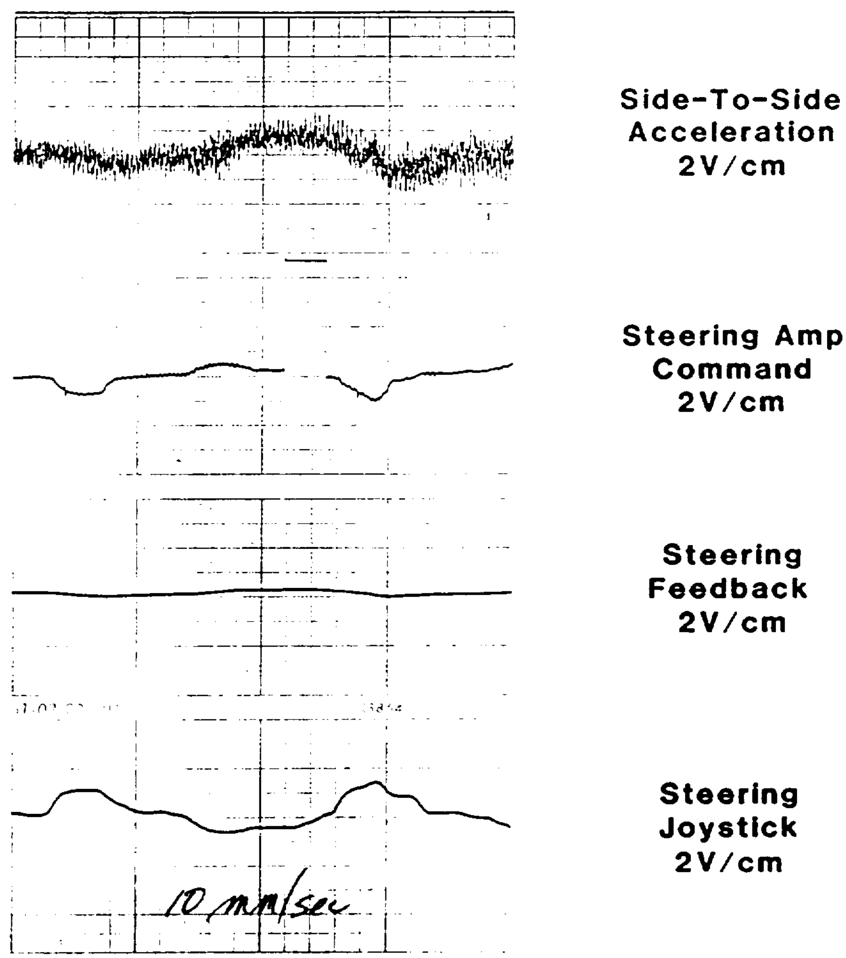


FIGURE C-105. TEST 3.2.2.5(d) RE-TEST

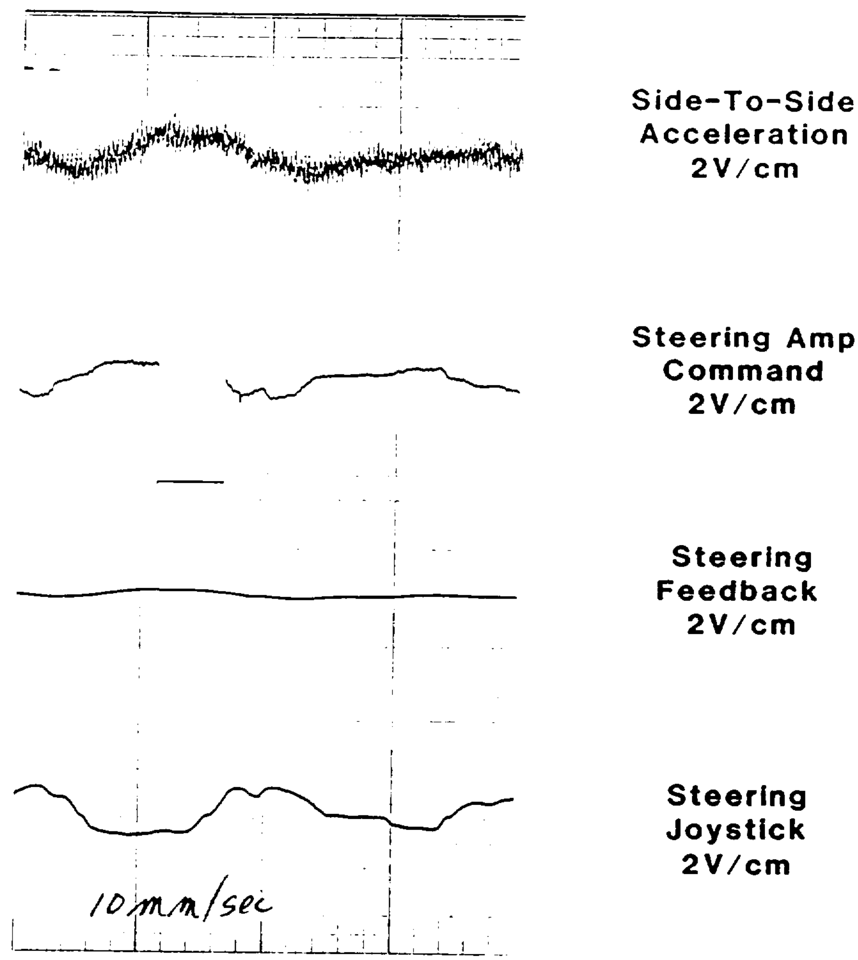


FIGURE C-106. TEST 3.2.2.5(e) RE-TEST

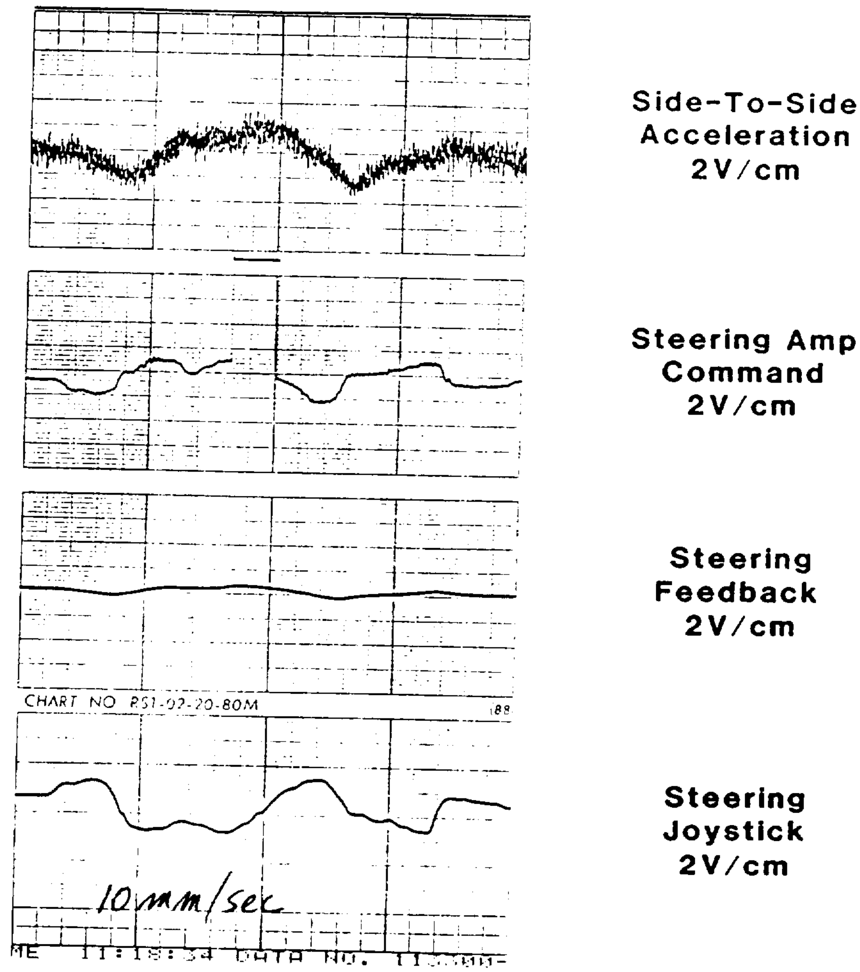


FIGURE C-107. TEST 3.2.2.5(f) RE-TEST

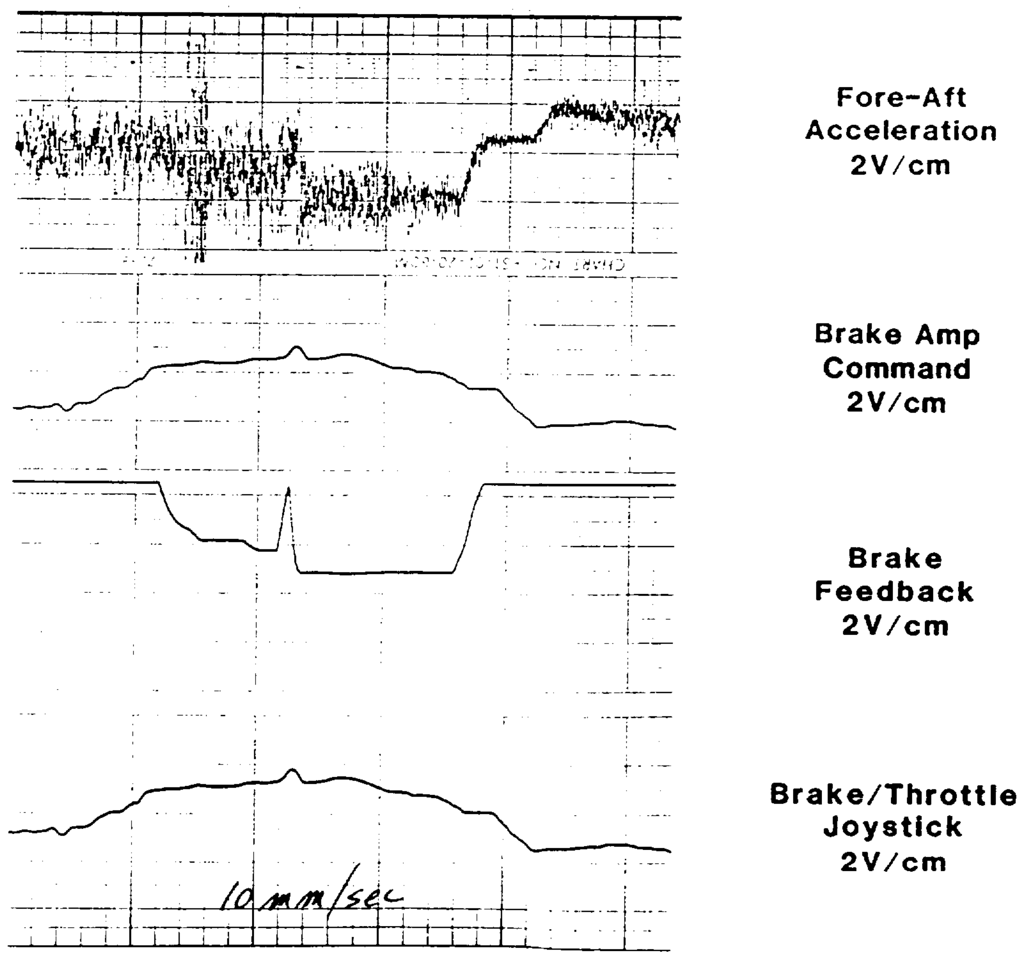
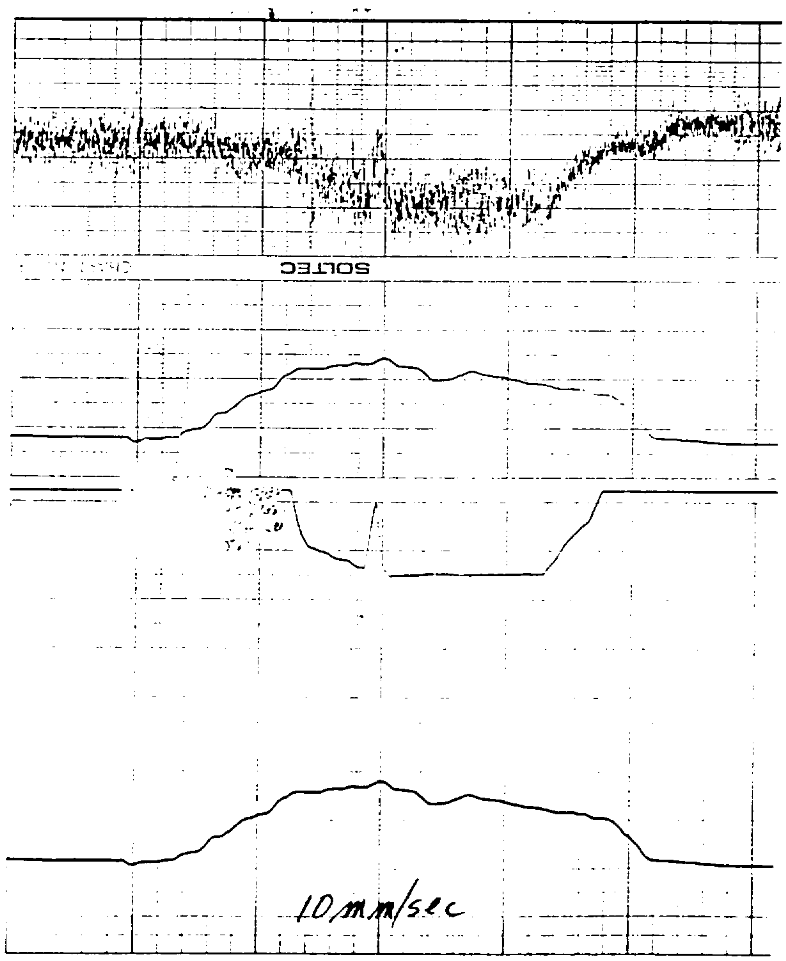


FIGURE C-108. TEST 3.2.3.1(a)



Fore-Aft Acceleration 2V/cm

Brake Amp Command 2V/cm

Brake Feedback 2V/cm

Brake/Throttle Joystick 2V/cm

FIGURE C-109. TEST 3.2.3.1(b)

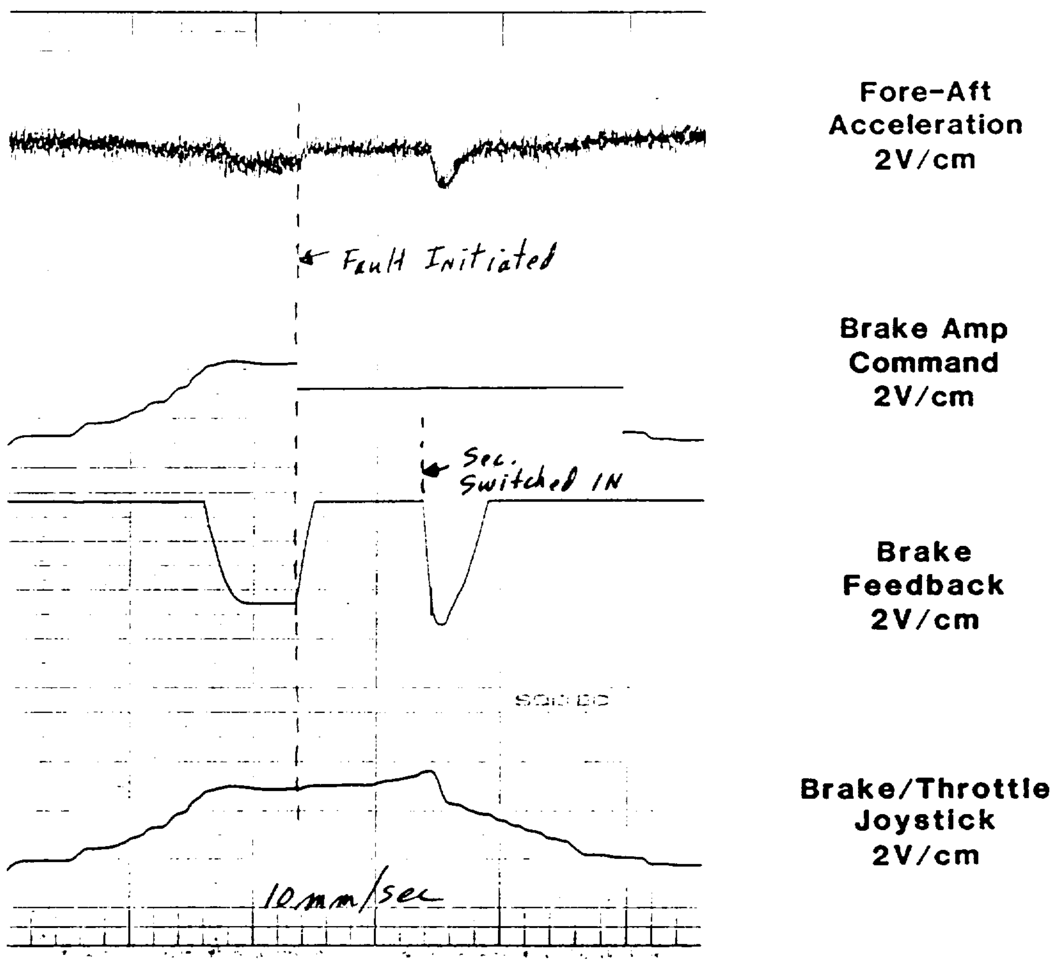


FIGURE C-110. TEST 3.2.3.2(a)

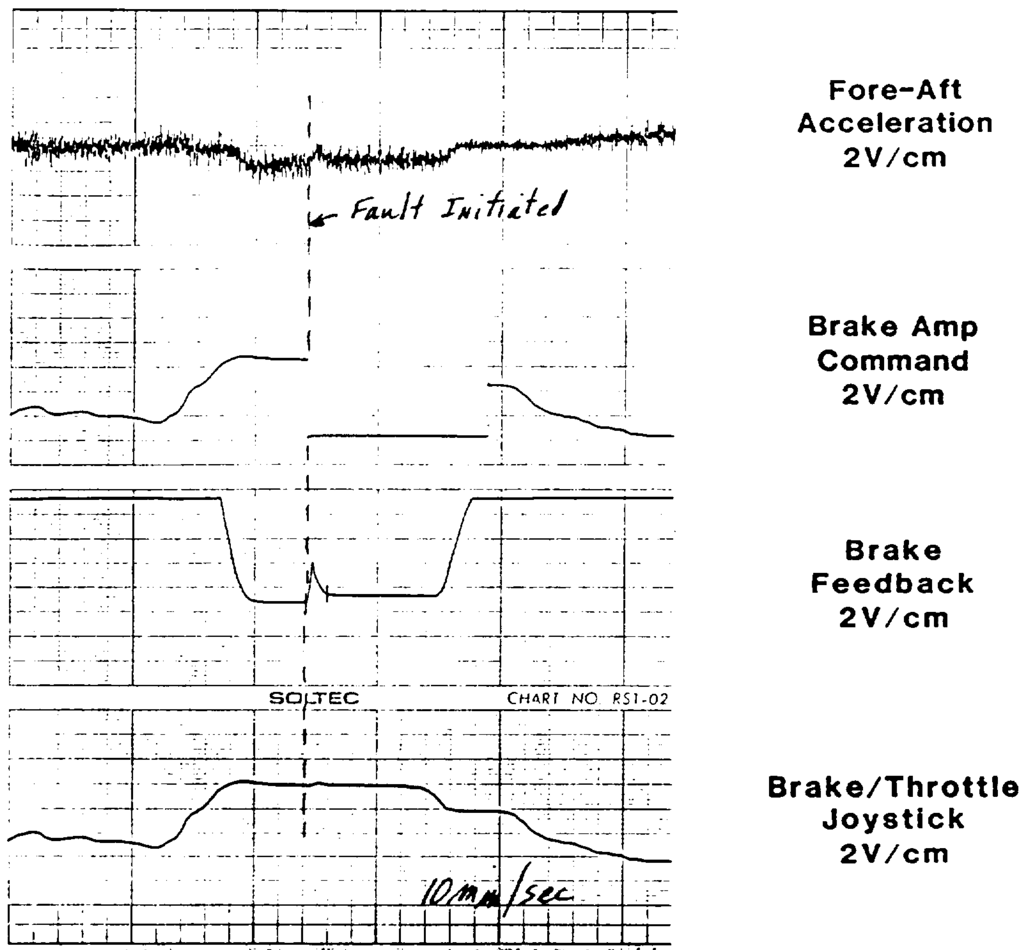


FIGURE C-111. TEST 3.2.3.2(b)

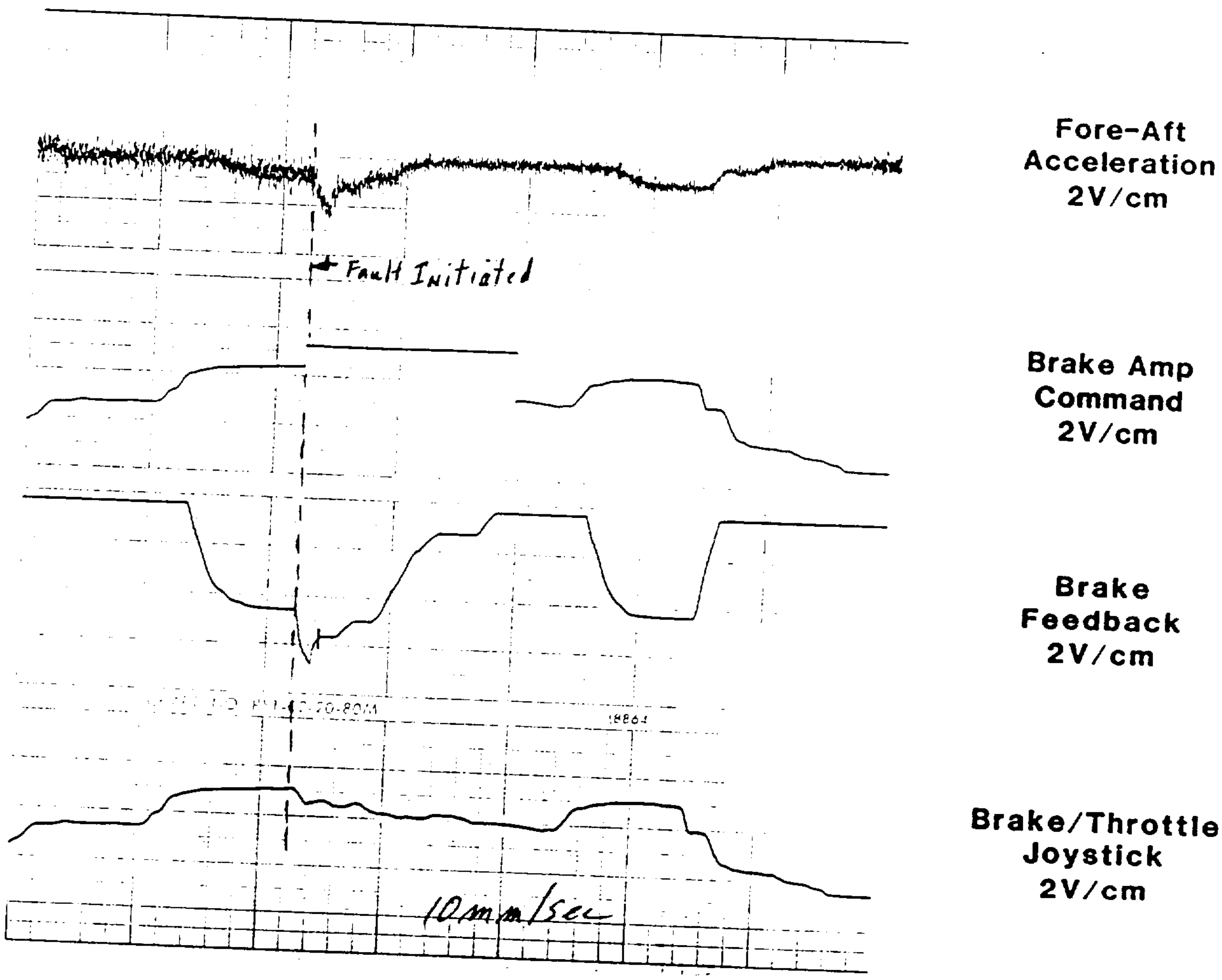


FIGURE C-112. TEST 3.2.3.2(c)

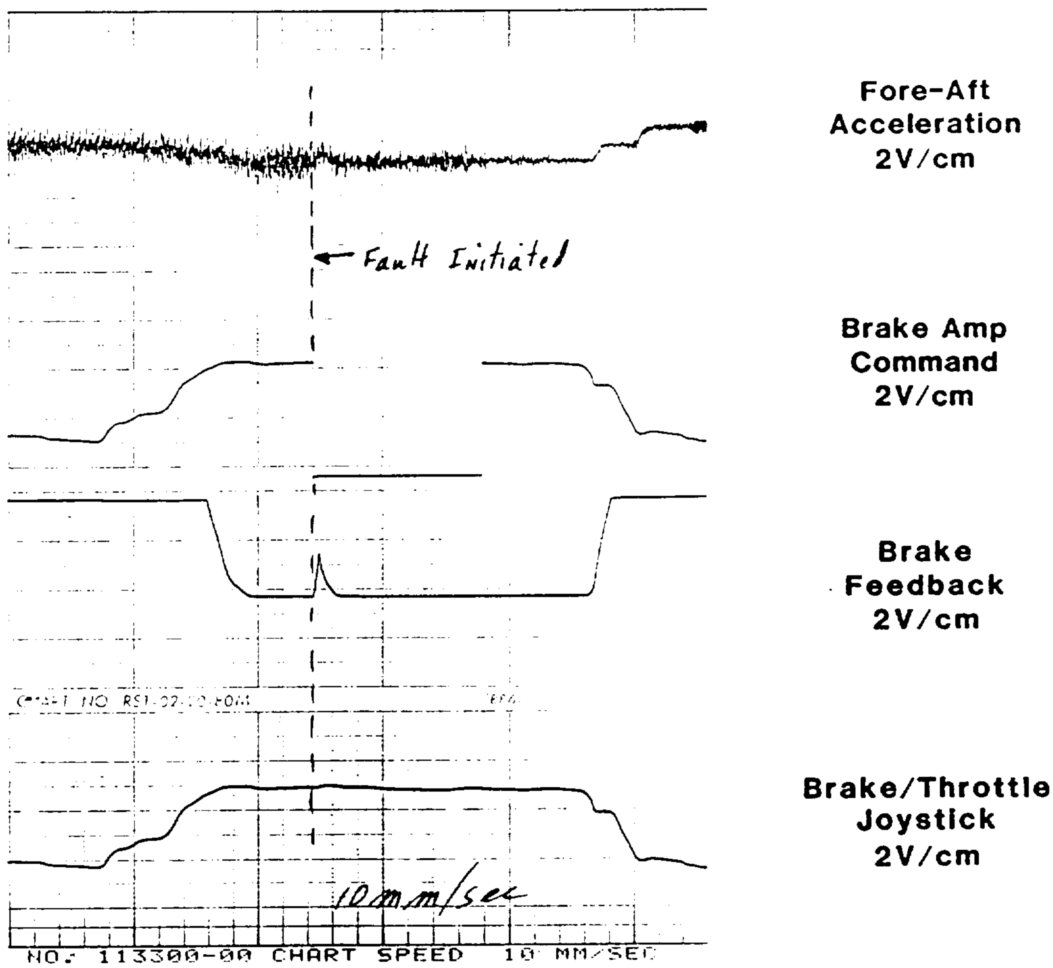


FIGURE C-113. TEST 3.2.3.2(d)

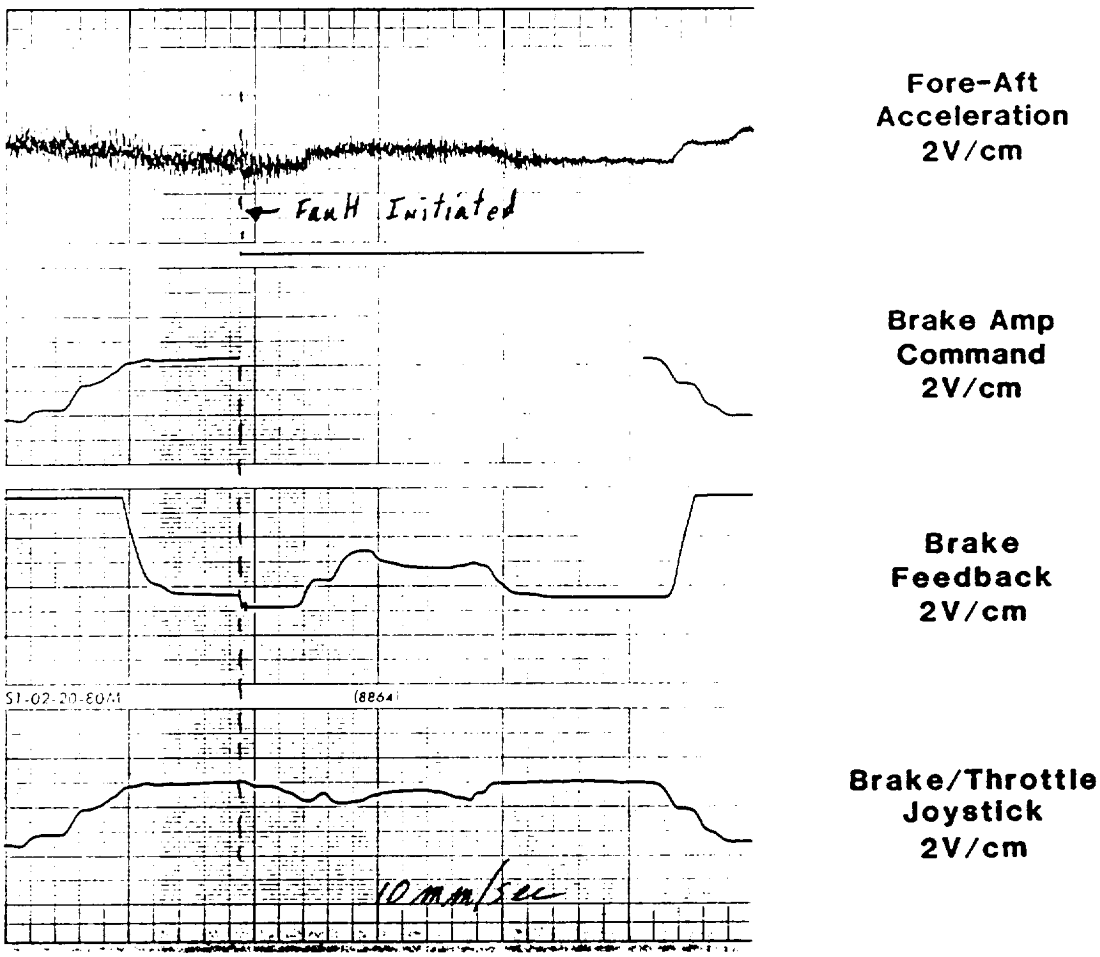


FIGURE C-114. TEST 3.2.3.2(e)

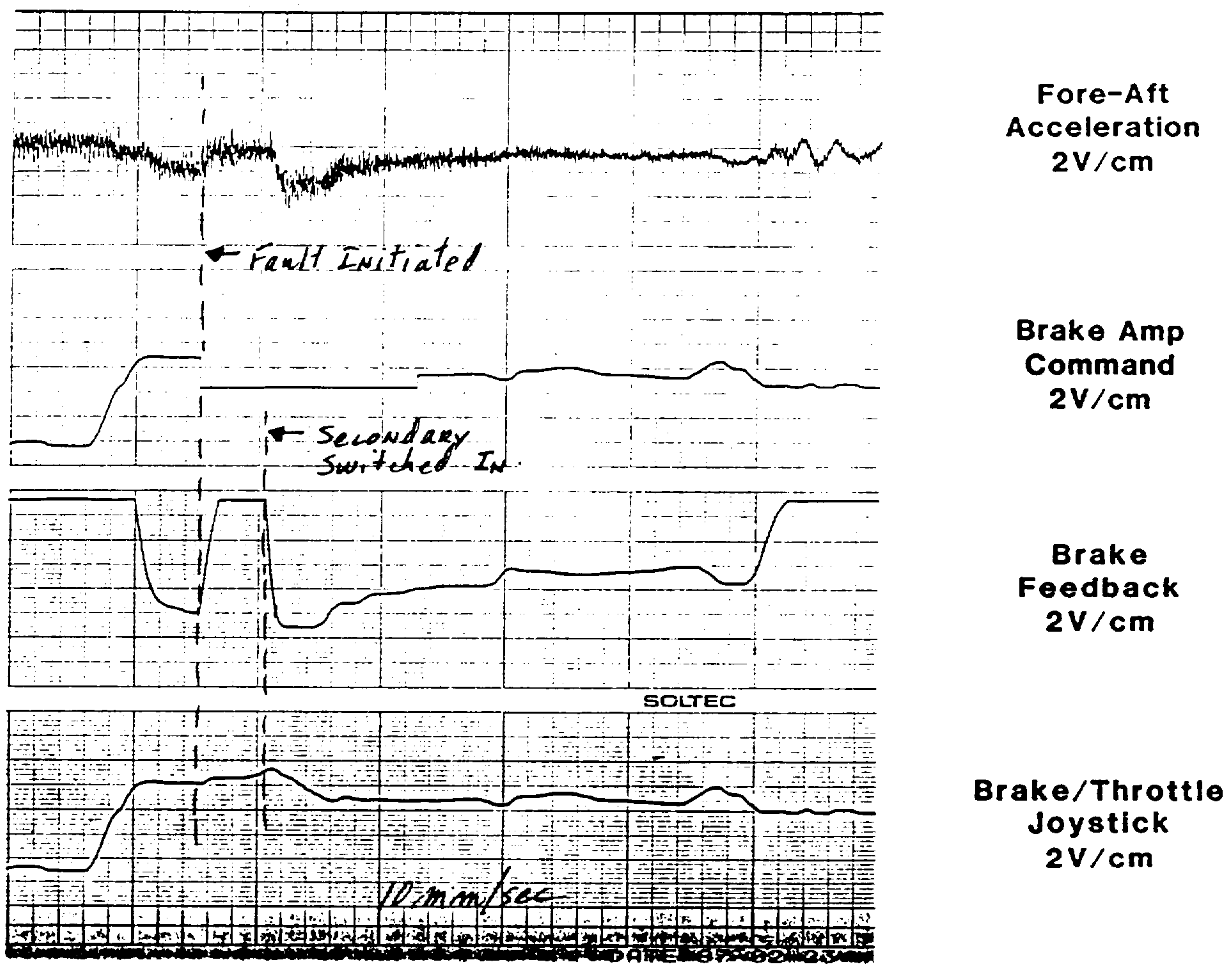


FIGURE C-115. TEST 3.2.3.2(f)

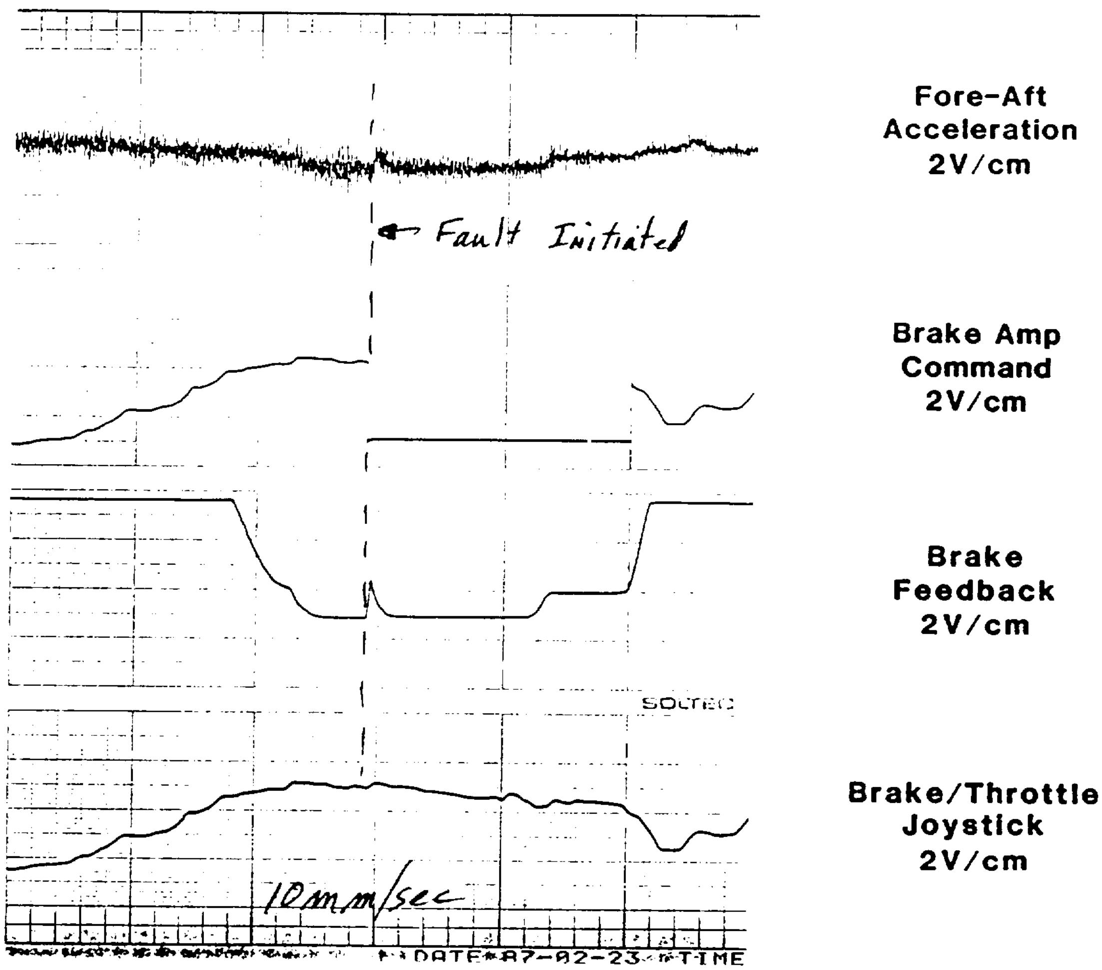


FIGURE C-116. TEST 3.2.3.2(g)

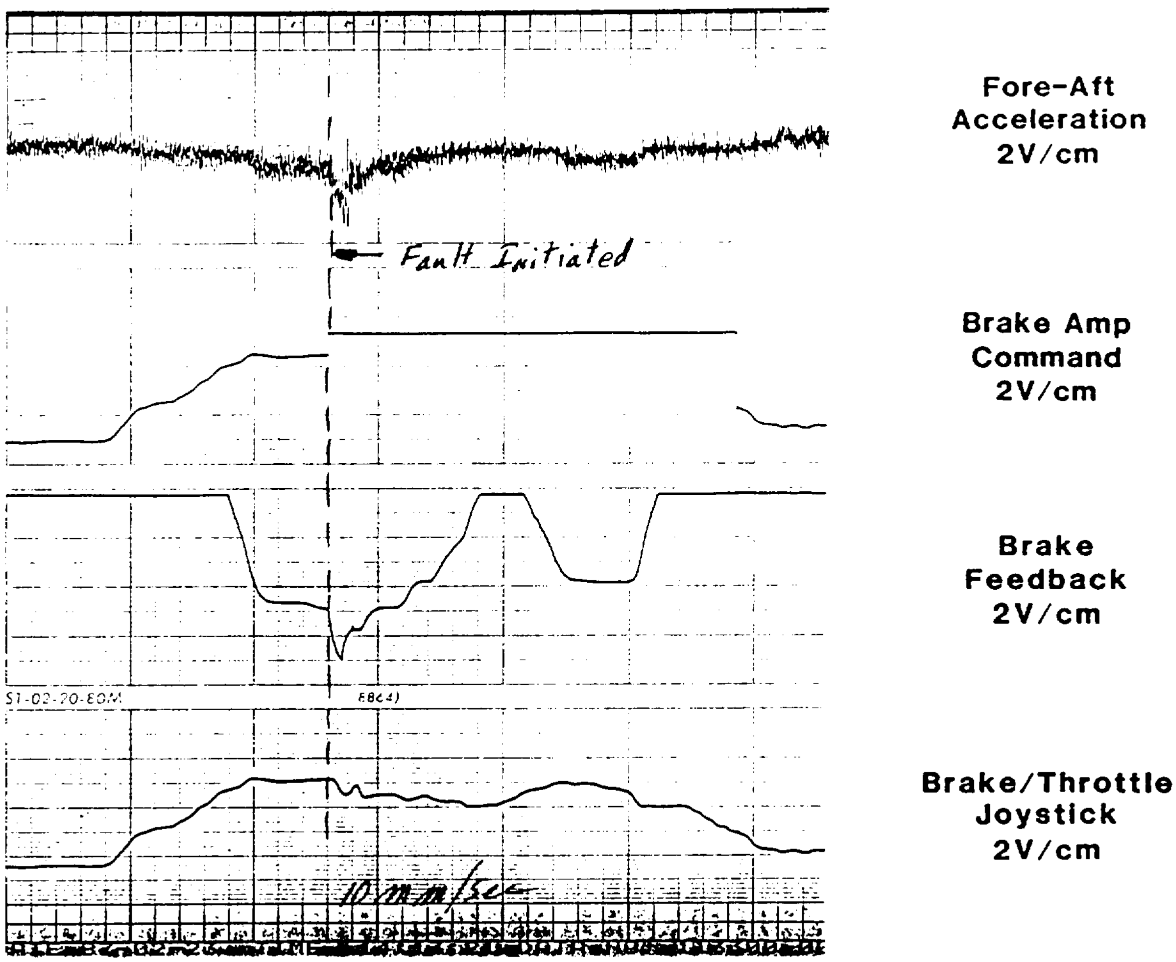
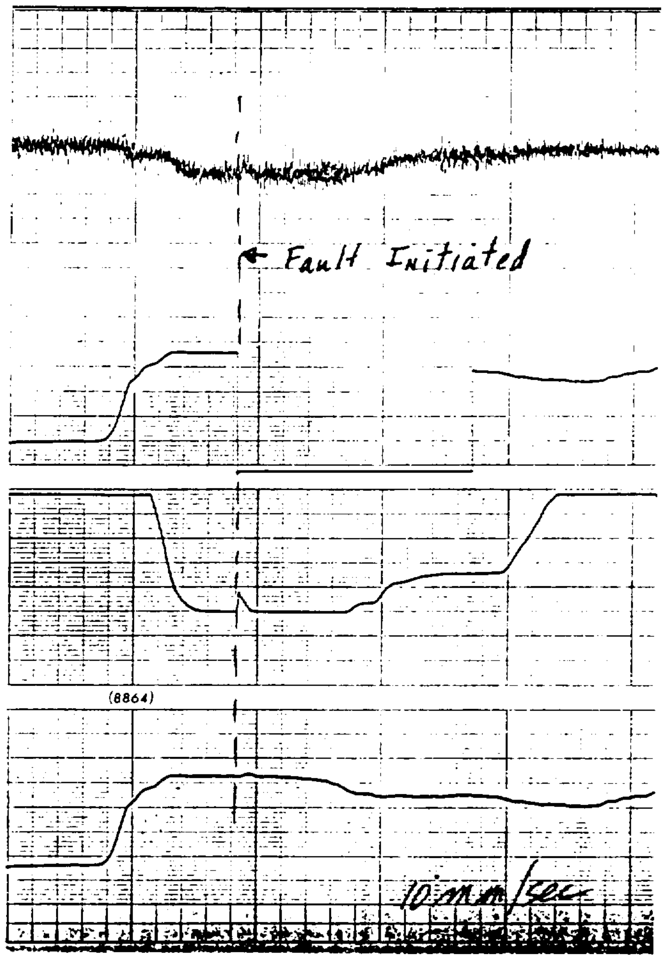


FIGURE C-117. TEST 3.2.3.2(h)



Fore-Aft Acceleration 2V/cm

Brake Amp Command 2V/cm

Brake Feedback 2V/cm

Brake/Throttle Joystick 2V/cm

FIGURE C-118. TEST 3.2.3.2(i)

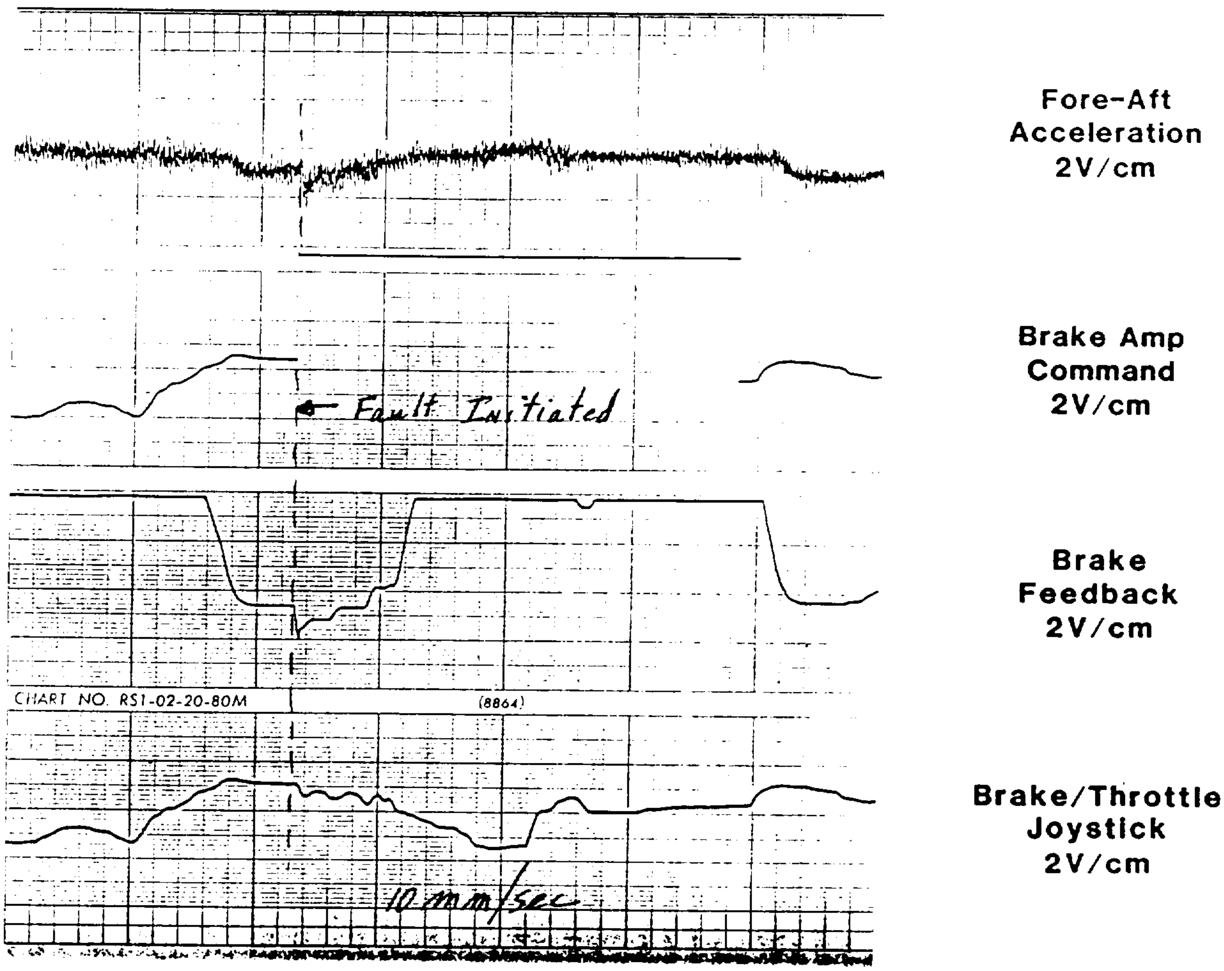


FIGURE C-119. TEST 3.2.3.2(j)

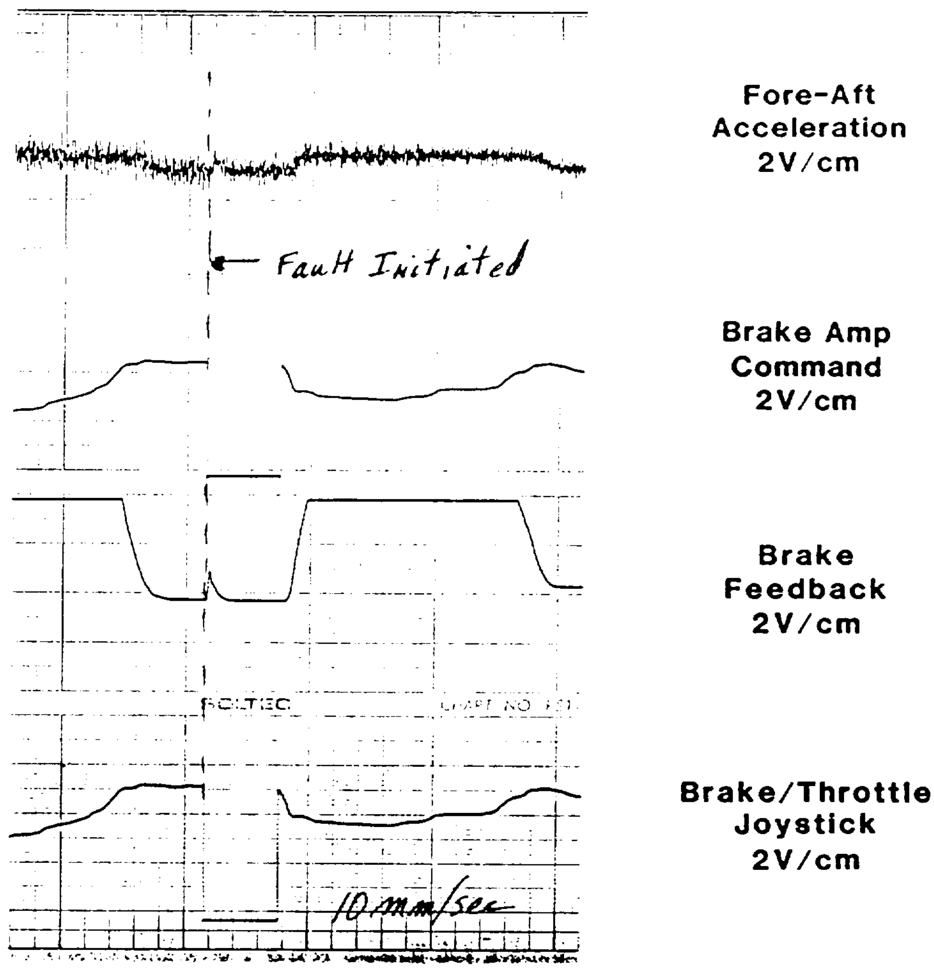


FIGURE C-120. TEST 3.2.3.3(a)

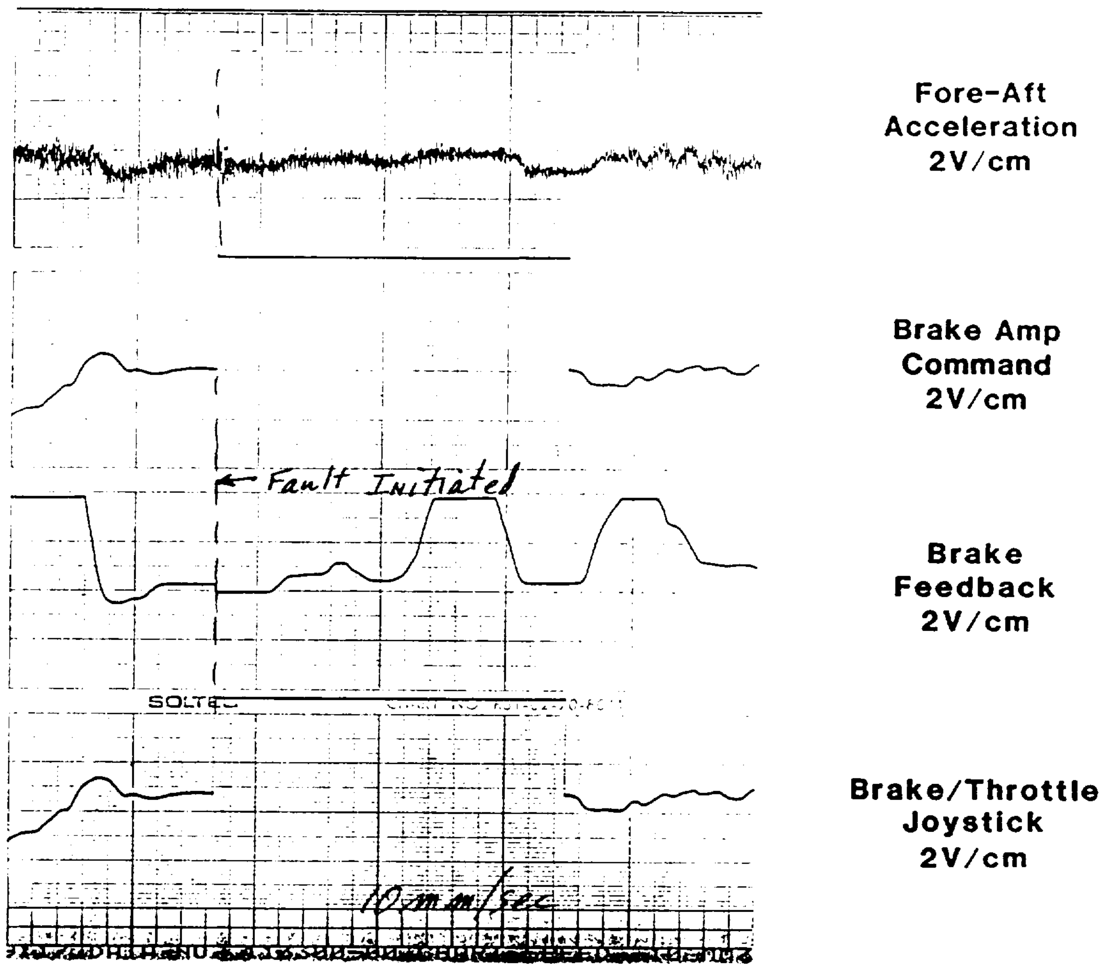


FIGURE C-121. TEST 3.2.3.3(b)

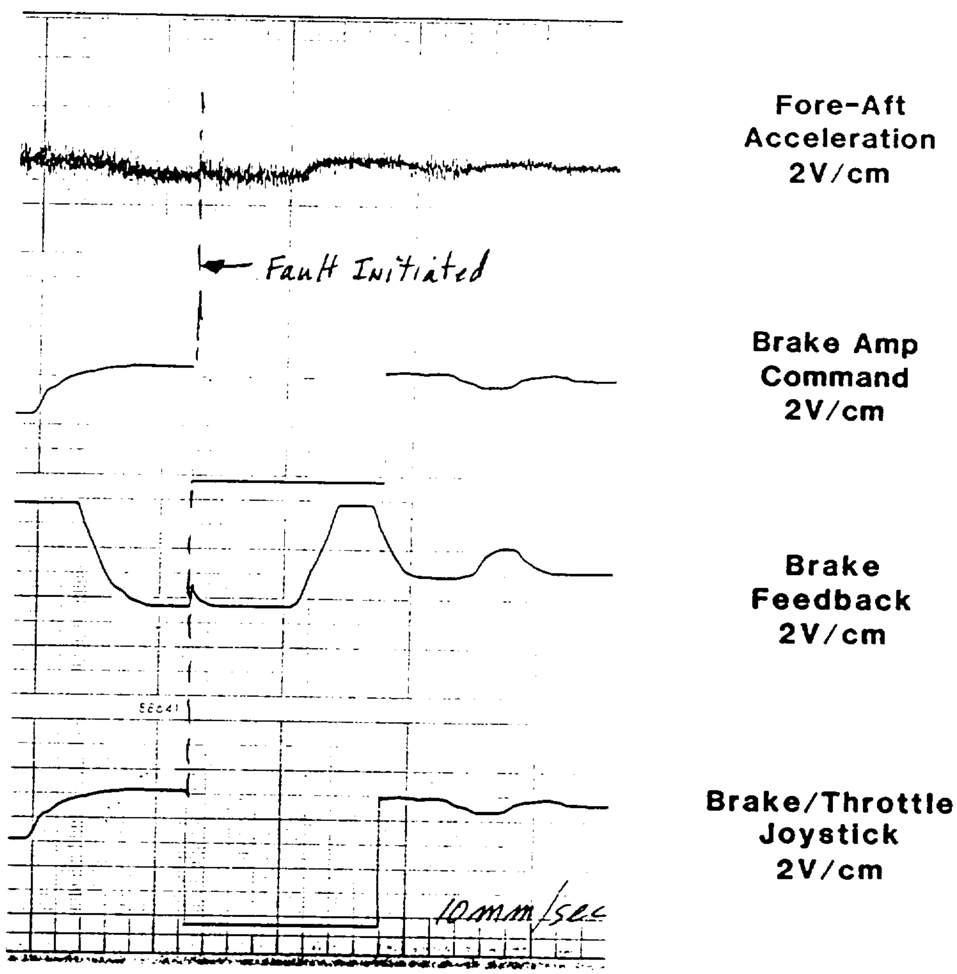


FIGURE C-122. TEST 3.2.3.3(c)

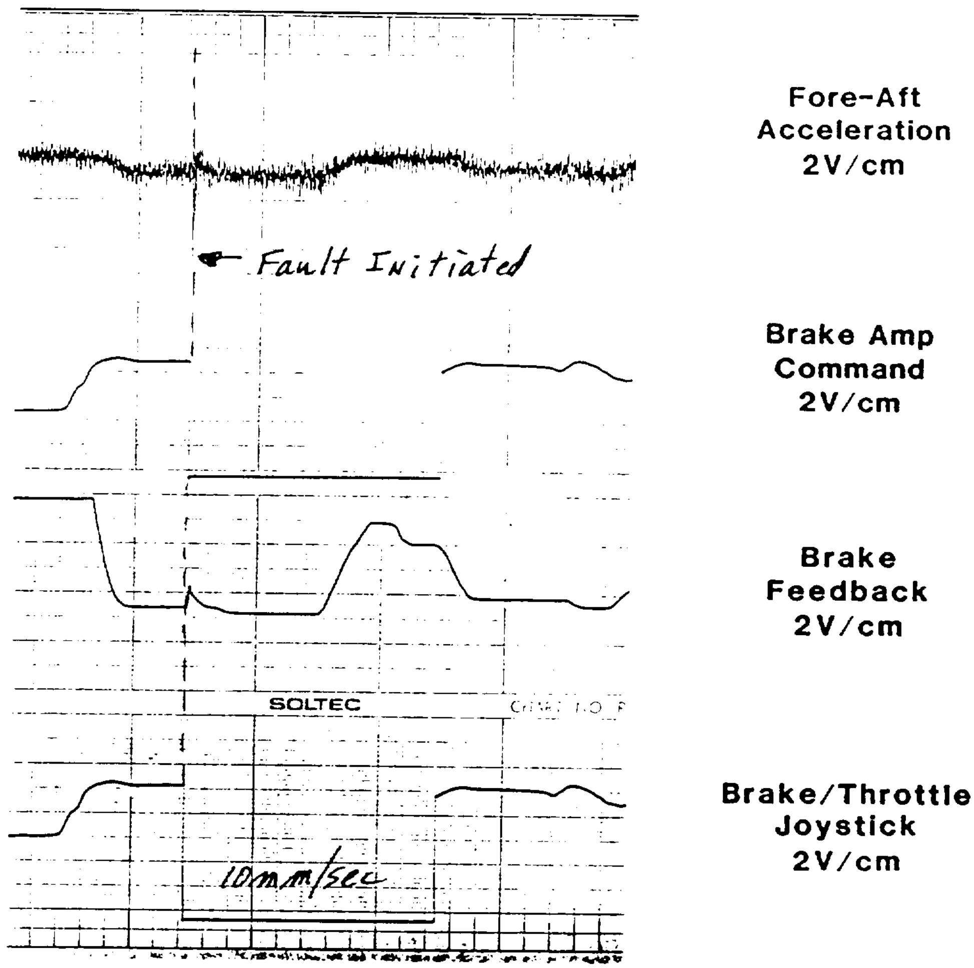


FIGURE C-123. TEST 3.2.3.3(d)

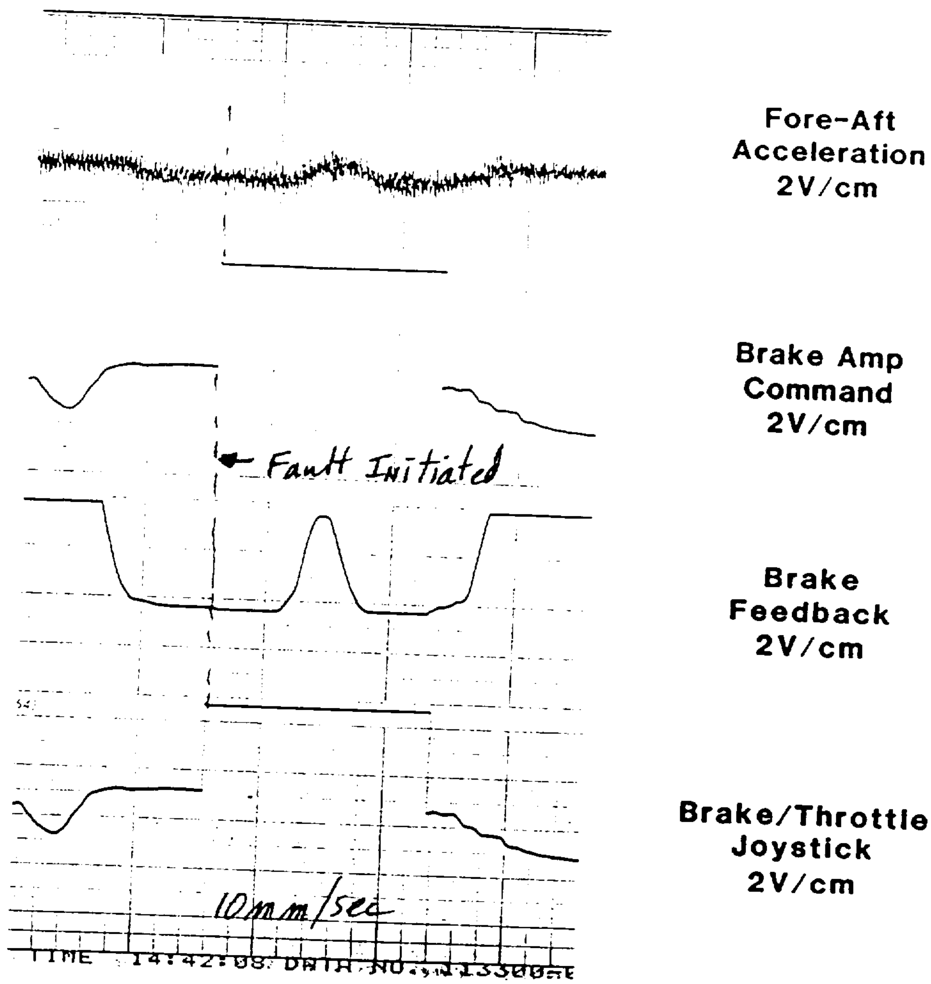


FIGURE C-124. TEST 3.2.3.3(e)

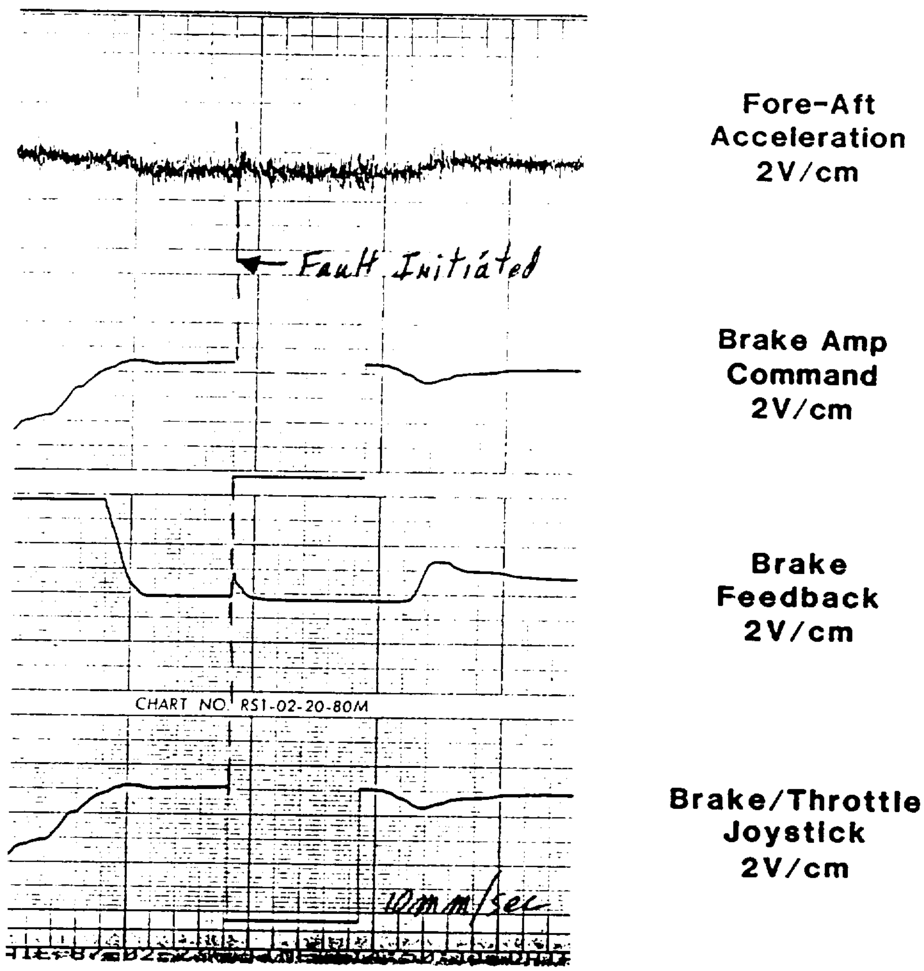


FIGURE C-125. TEST 3.2.3.3(f)

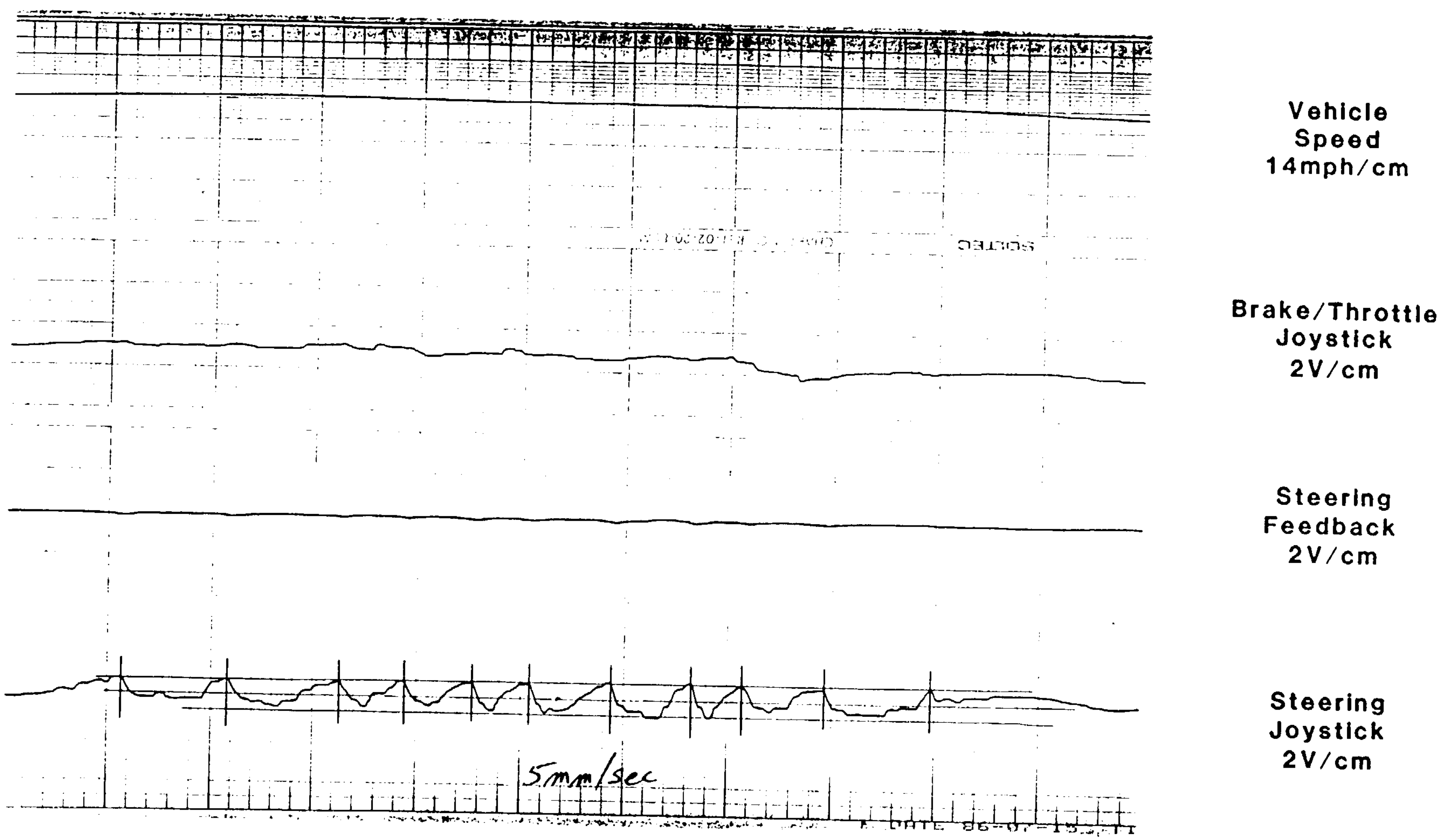


FIGURE C-126. VANCOUVER ROAD TEST - JULY 15, 1986 (A.M.)

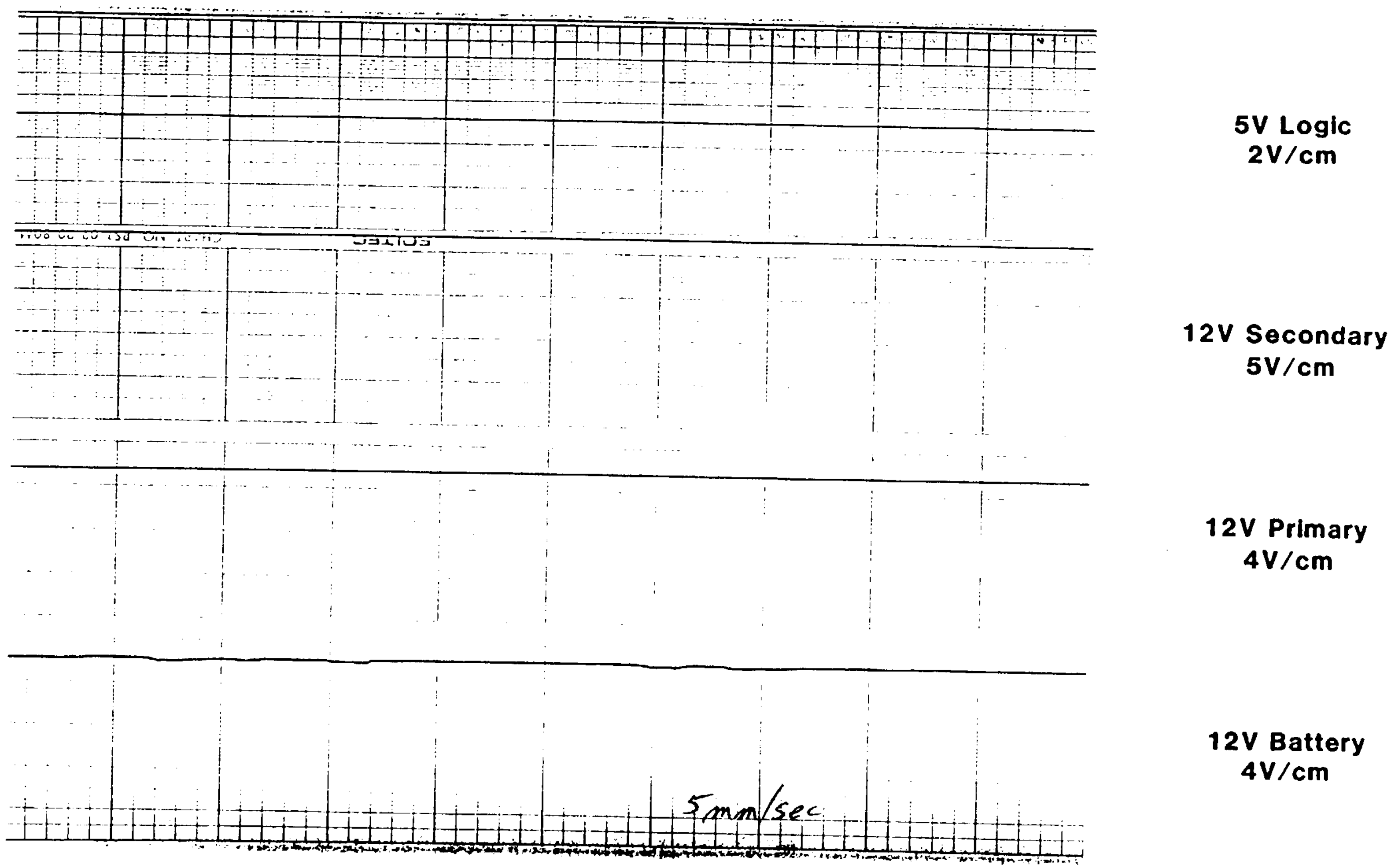


FIGURE C-127. VANCOUVER ROAD TEST - JULY 15, 1986 (A.M.)

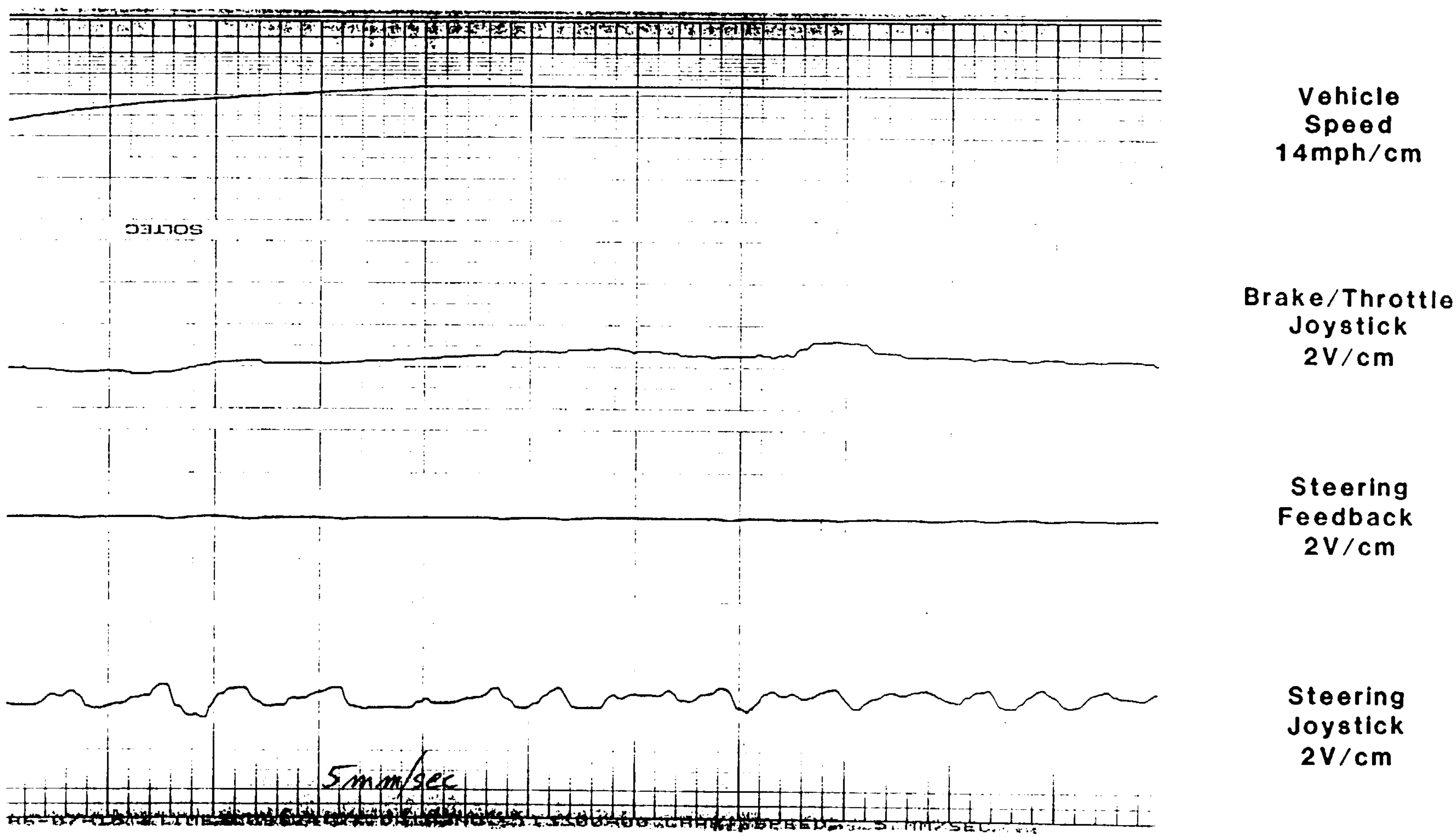


FIGURE C-128. VANCOUVER ROAD TEST - JULY 15, 1986 (A.M.)

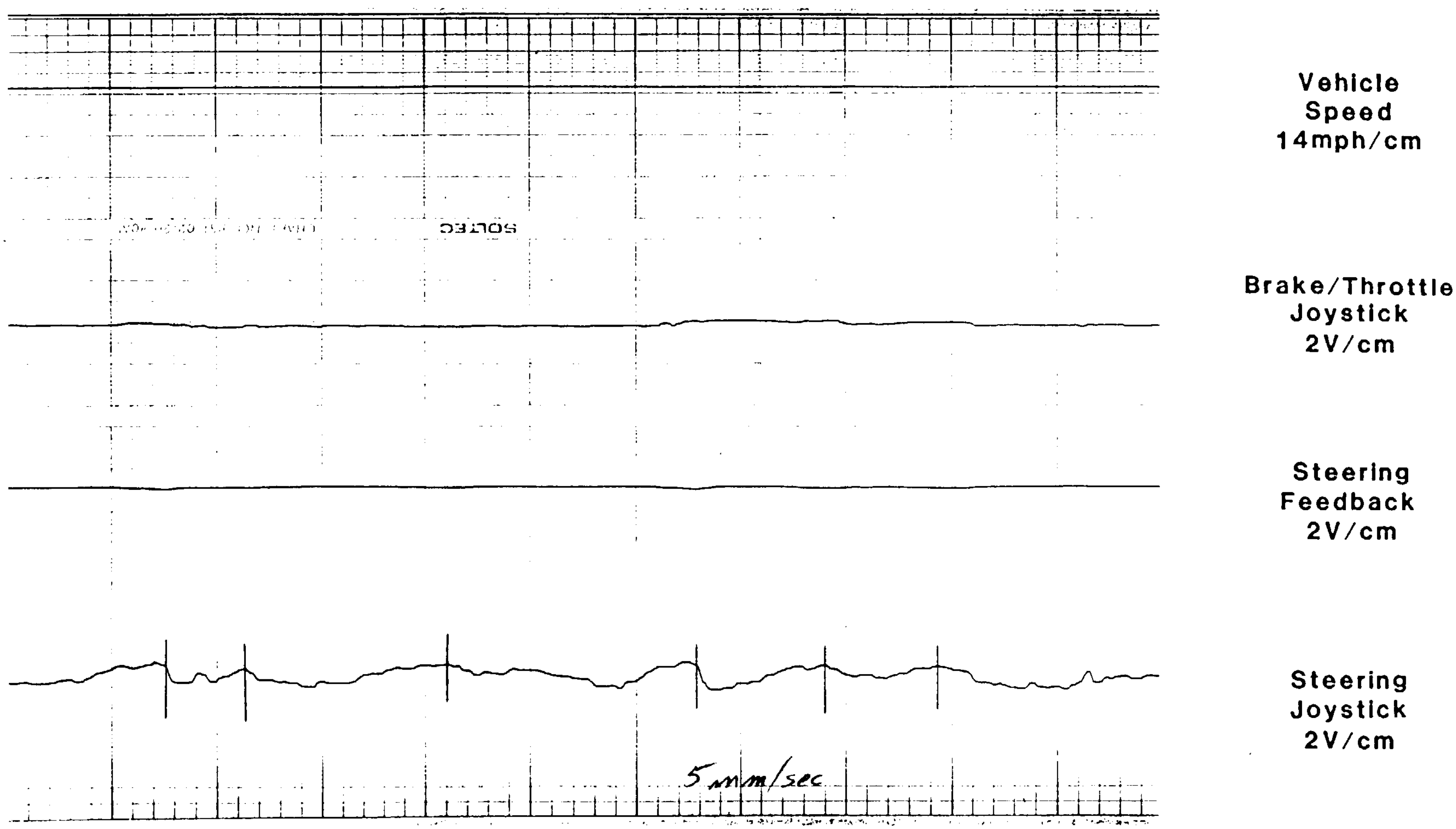


FIGURE C-129. VANCOUVER ROAD TEST - JULY 15, 1986 (P.M.)

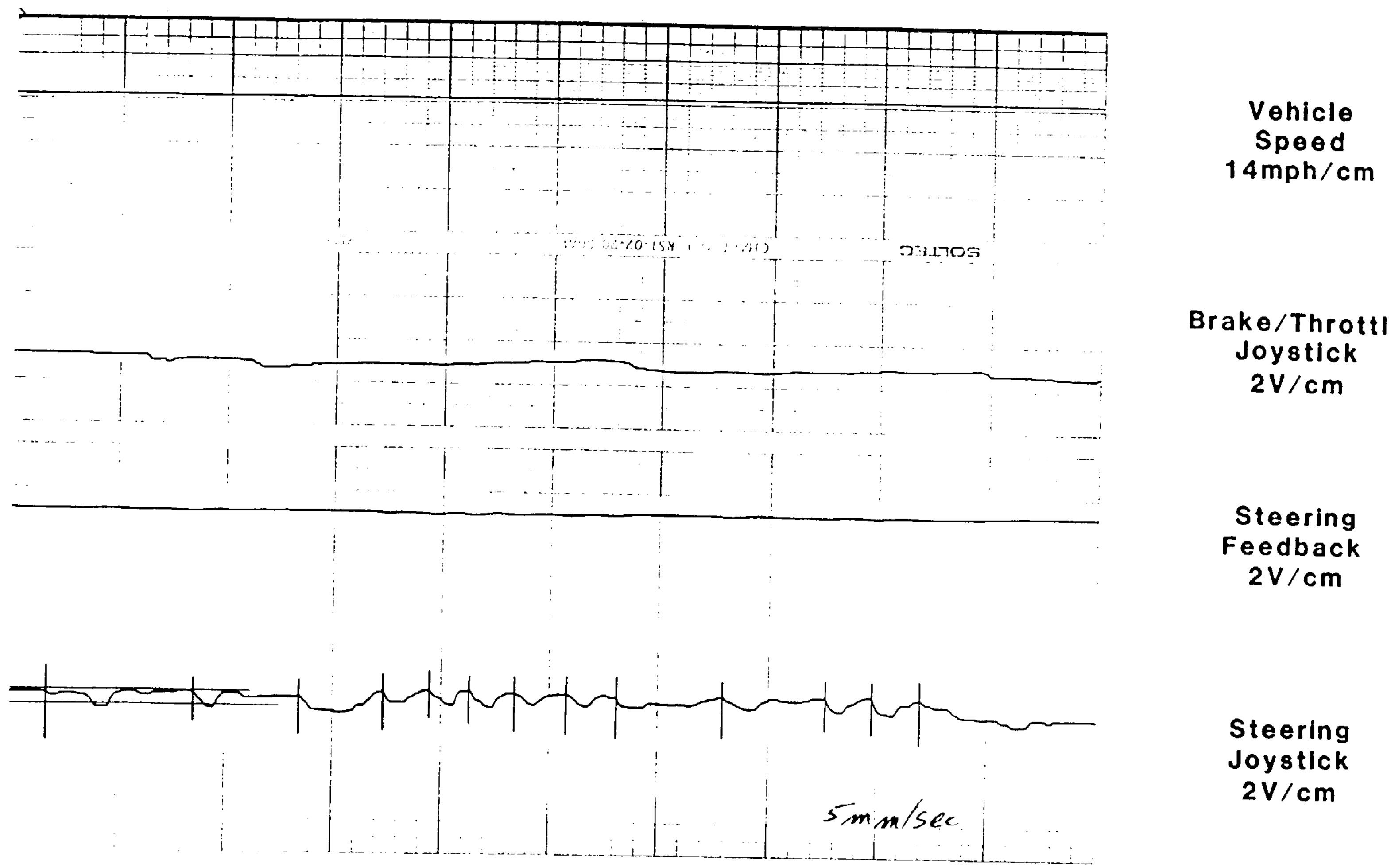


FIGURE C-130. VANCOUVER ROAD TEST - JULY 16, 1986 (A.M.)

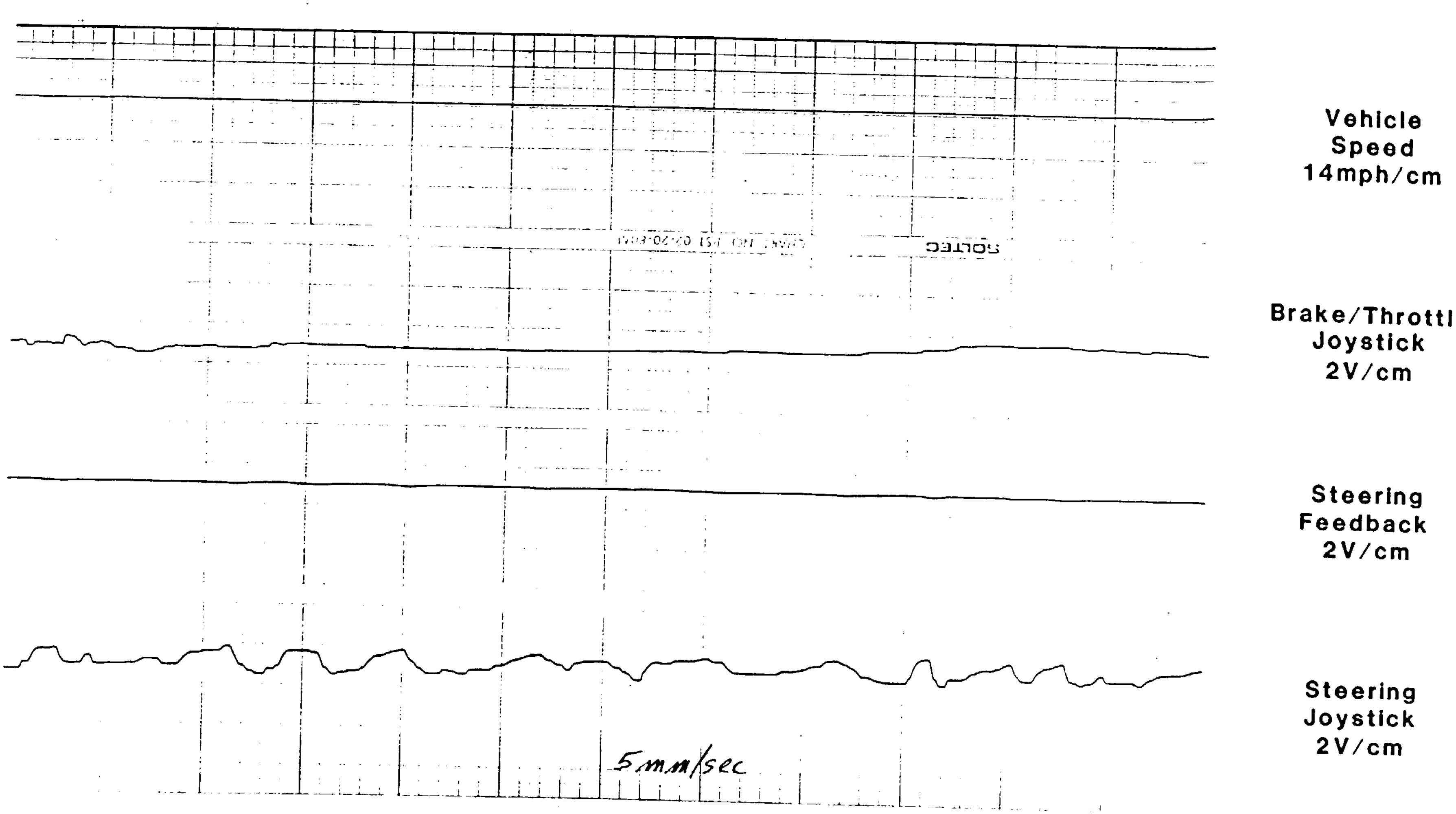


FIGURE C-131. VANCOUVER ROAD TEST - JULY 16, 1986 (P.M.)

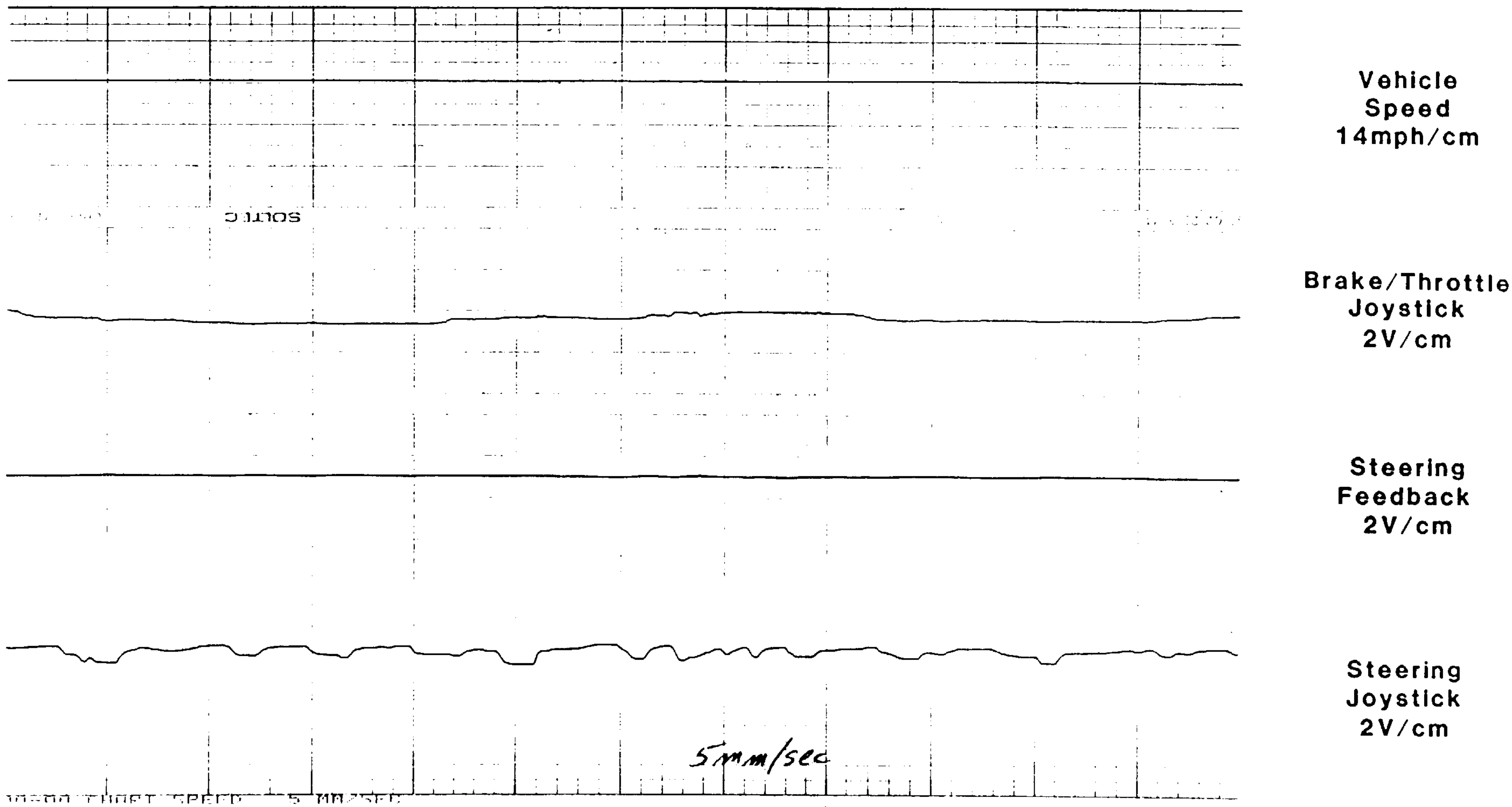


FIGURE C-132. VANCOUVER ROAD TEST - JULY 17, 1986 (A.M.)

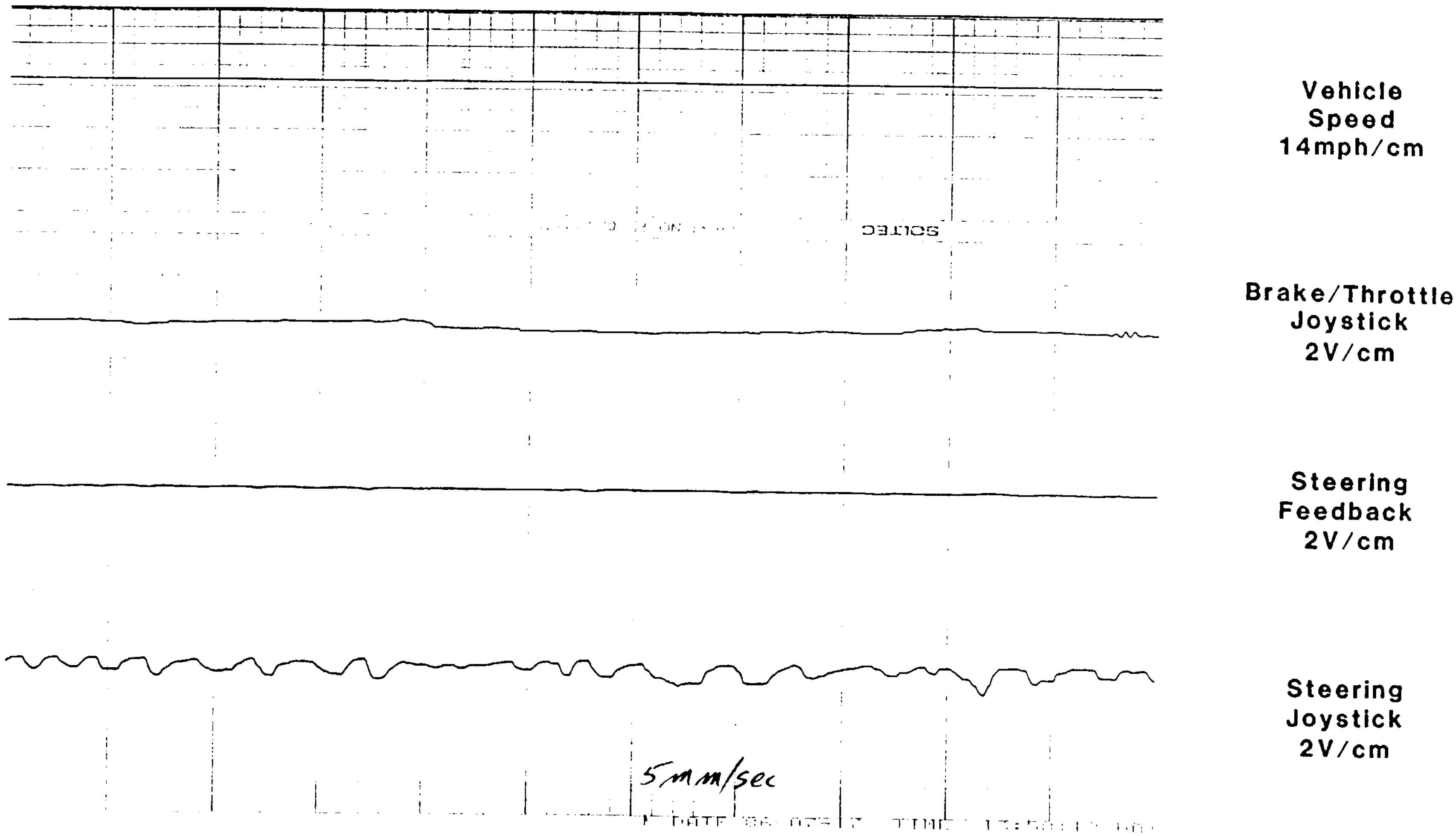


FIGURE C-133. VANCOUVER ROAD TEST - JULY 17, 1986 (P.M.)

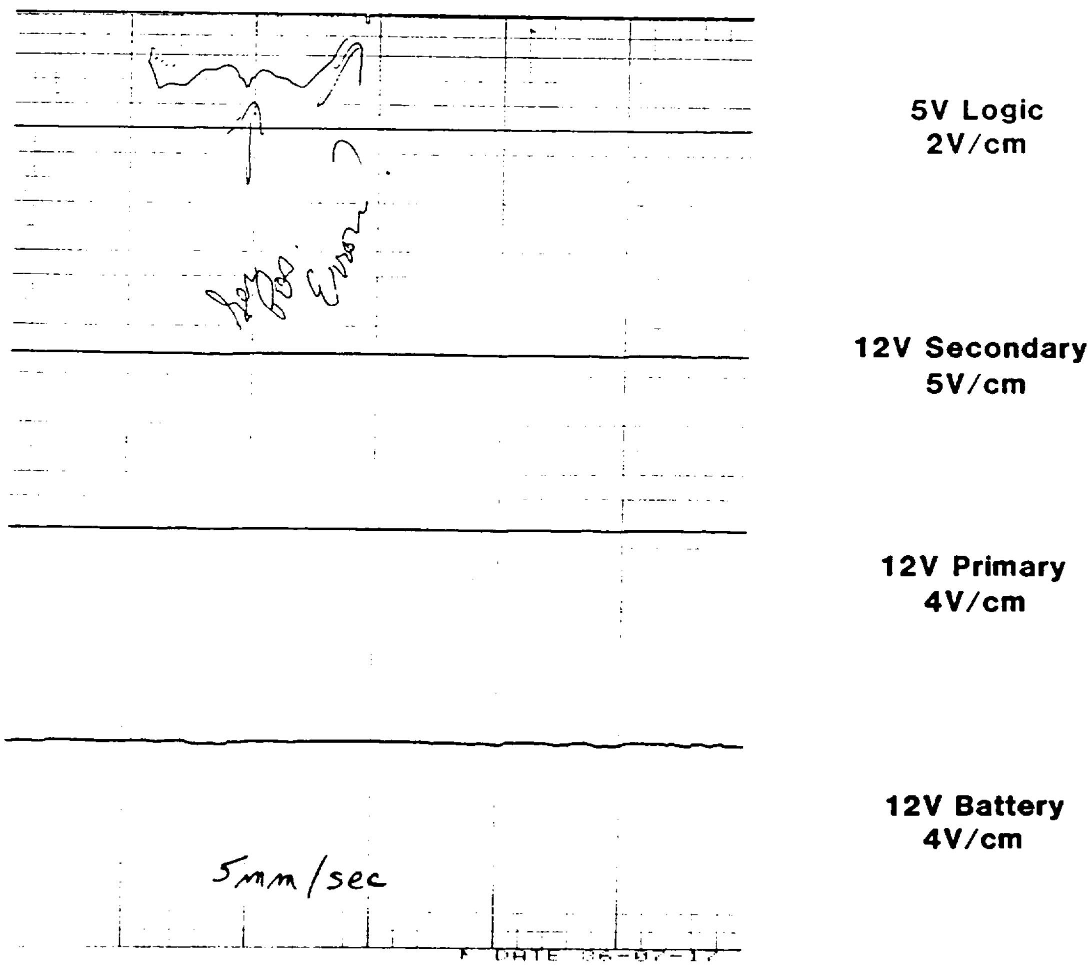


FIGURE C-134. VANCOUVER ROAD TEST - JULY 17, 1986 (A.M.)

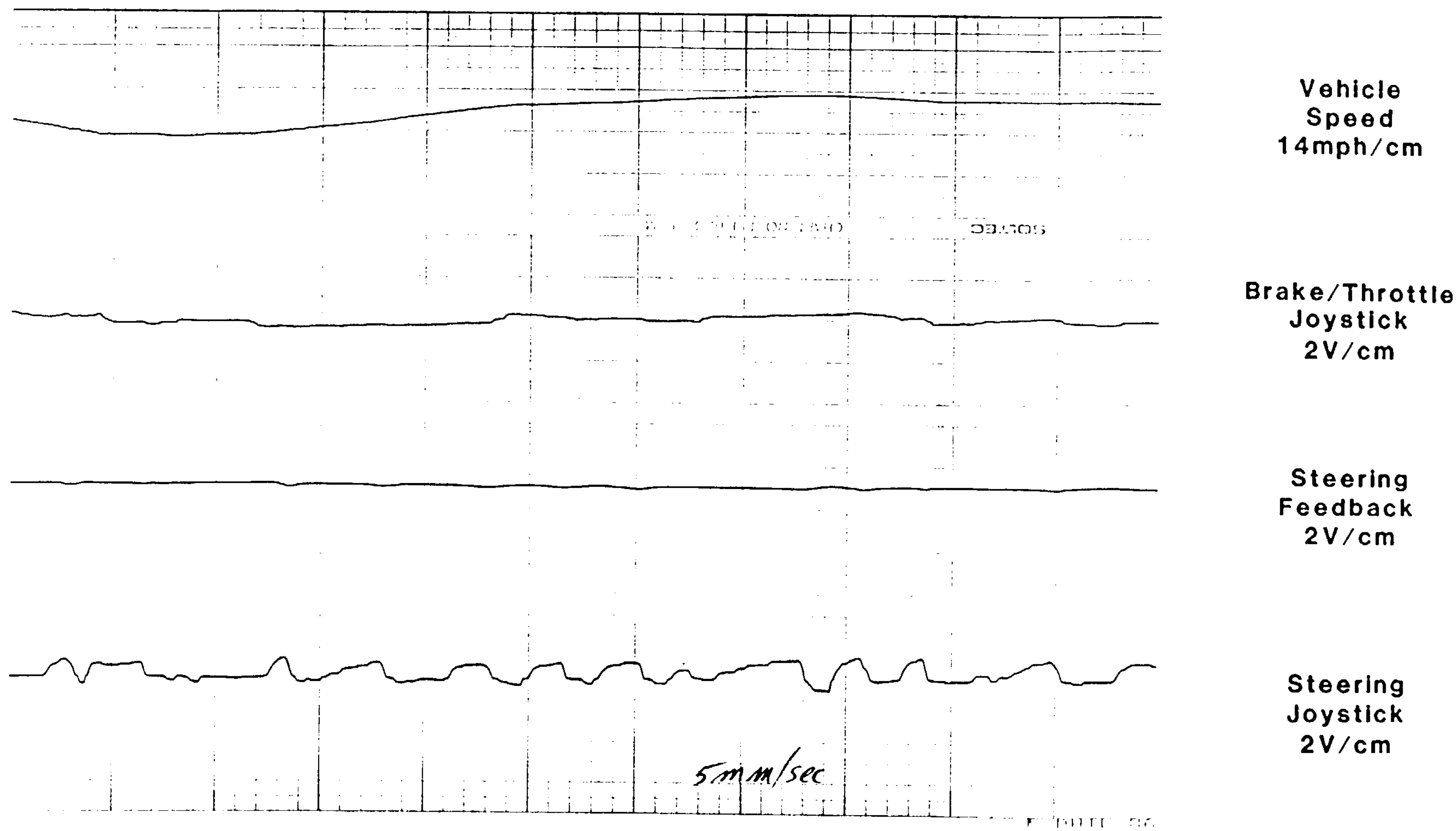


FIGURE C-135. VANCOUVER ROAD TEST - JULY 26, 1986 (A.M.)

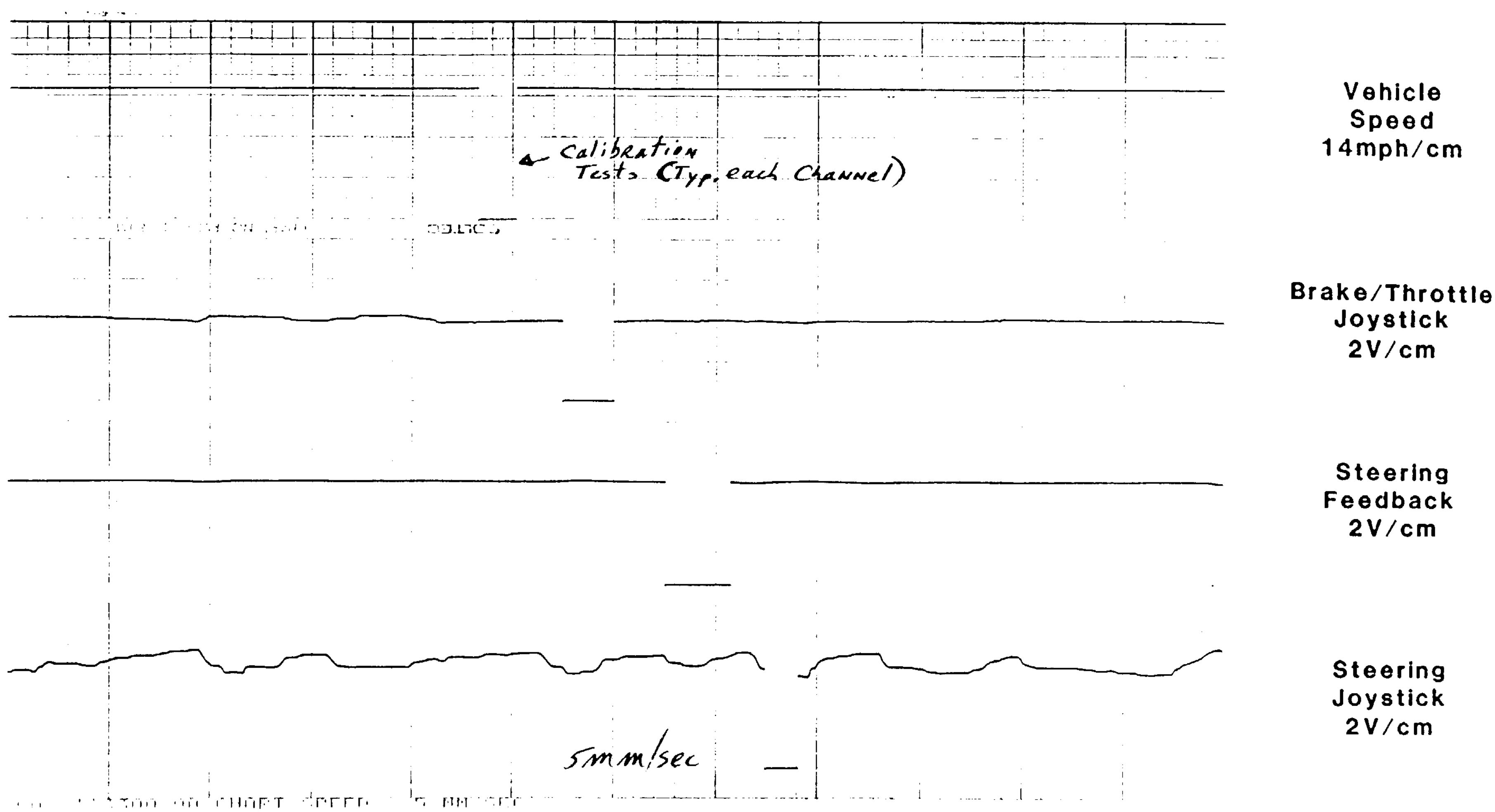


FIGURE C-136. VANCOUVER ROAD TEST - JULY 26, 1986 (A.M.)

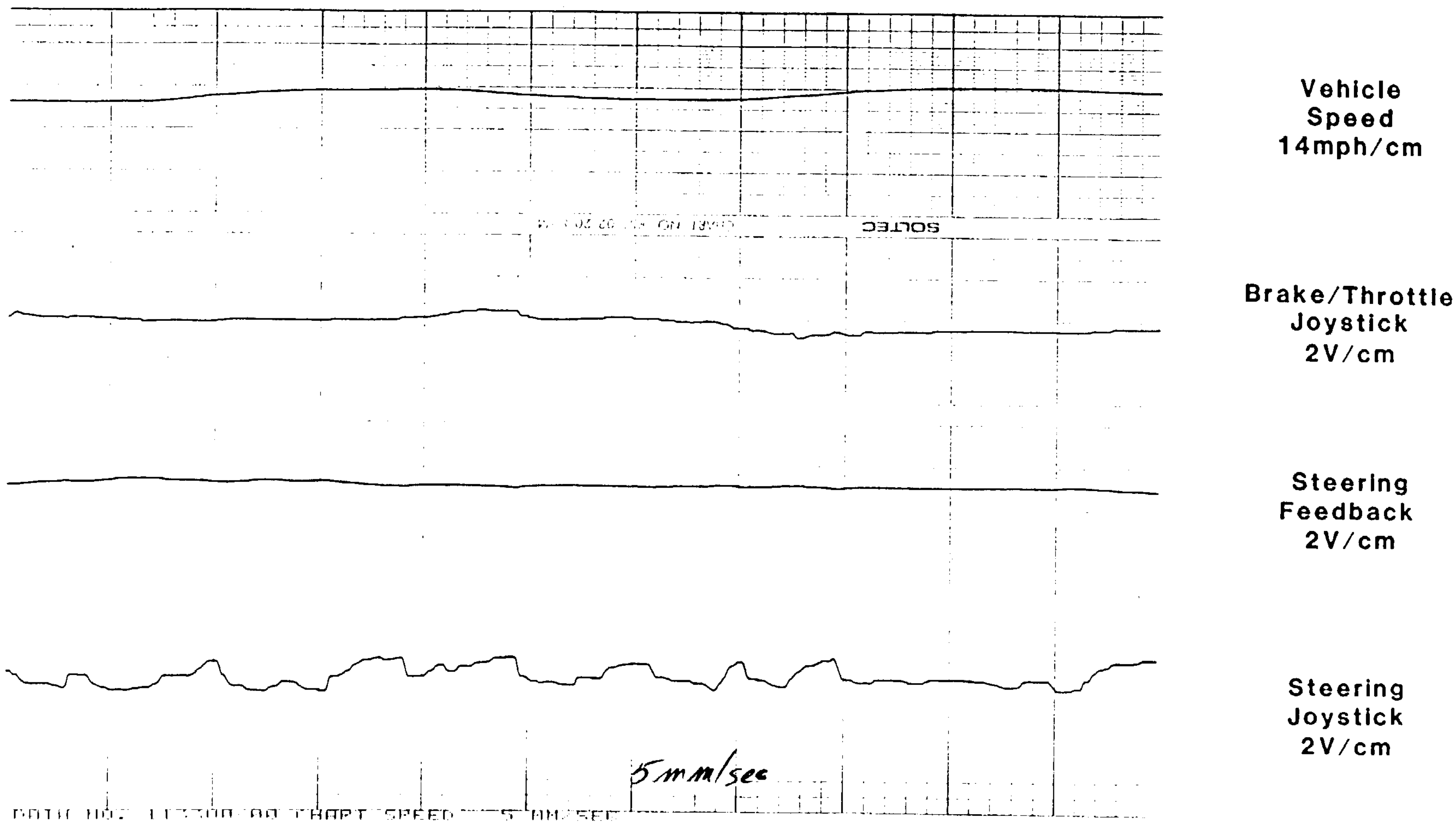


FIGURE C-137. VANCOUVER ROAD TEST - JULY 27, 1986 (A.M.)

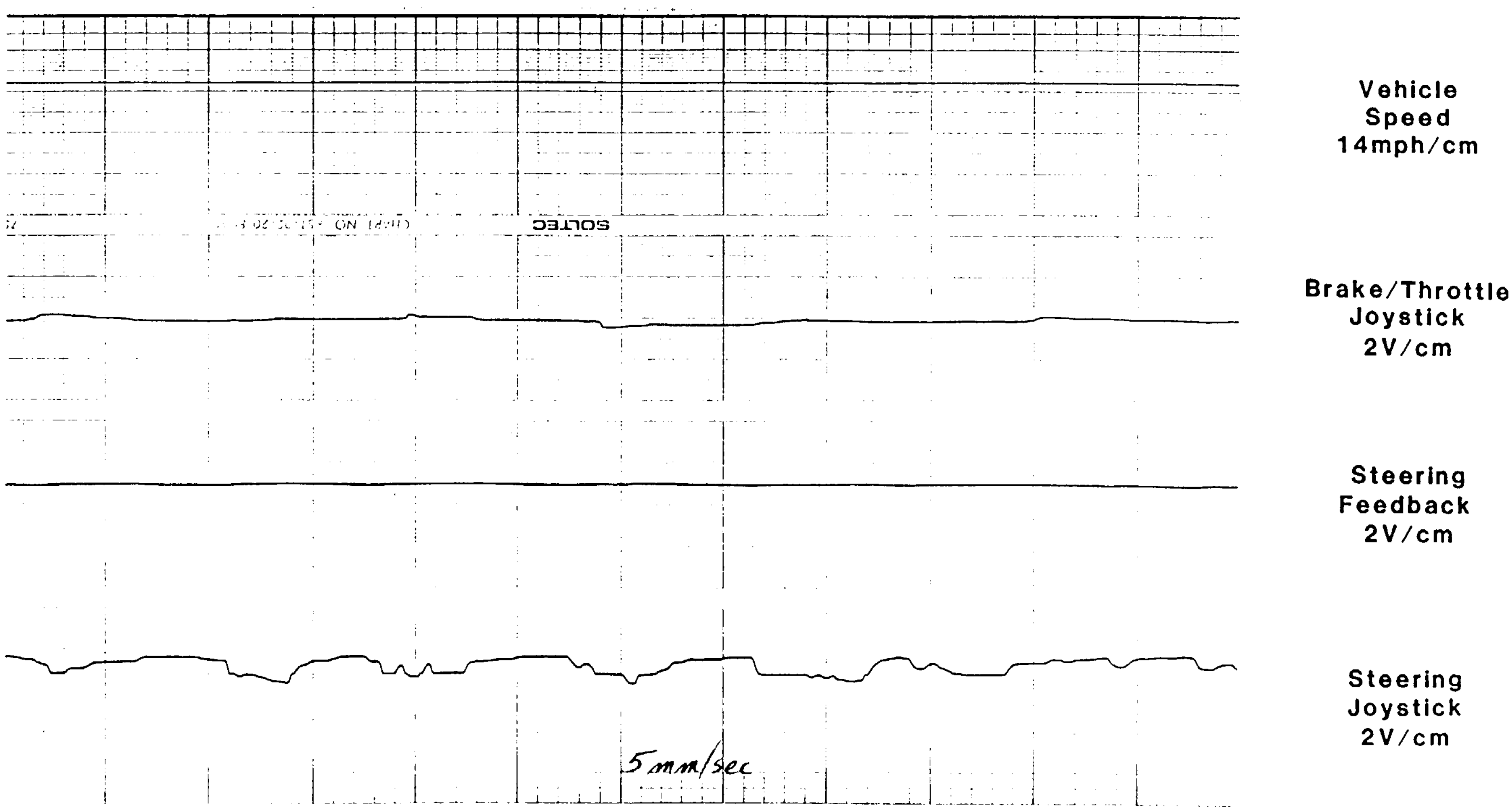


FIGURE C-138. VANCOUVER ROAD TEST - JULY 27, 1986 (P.M.)

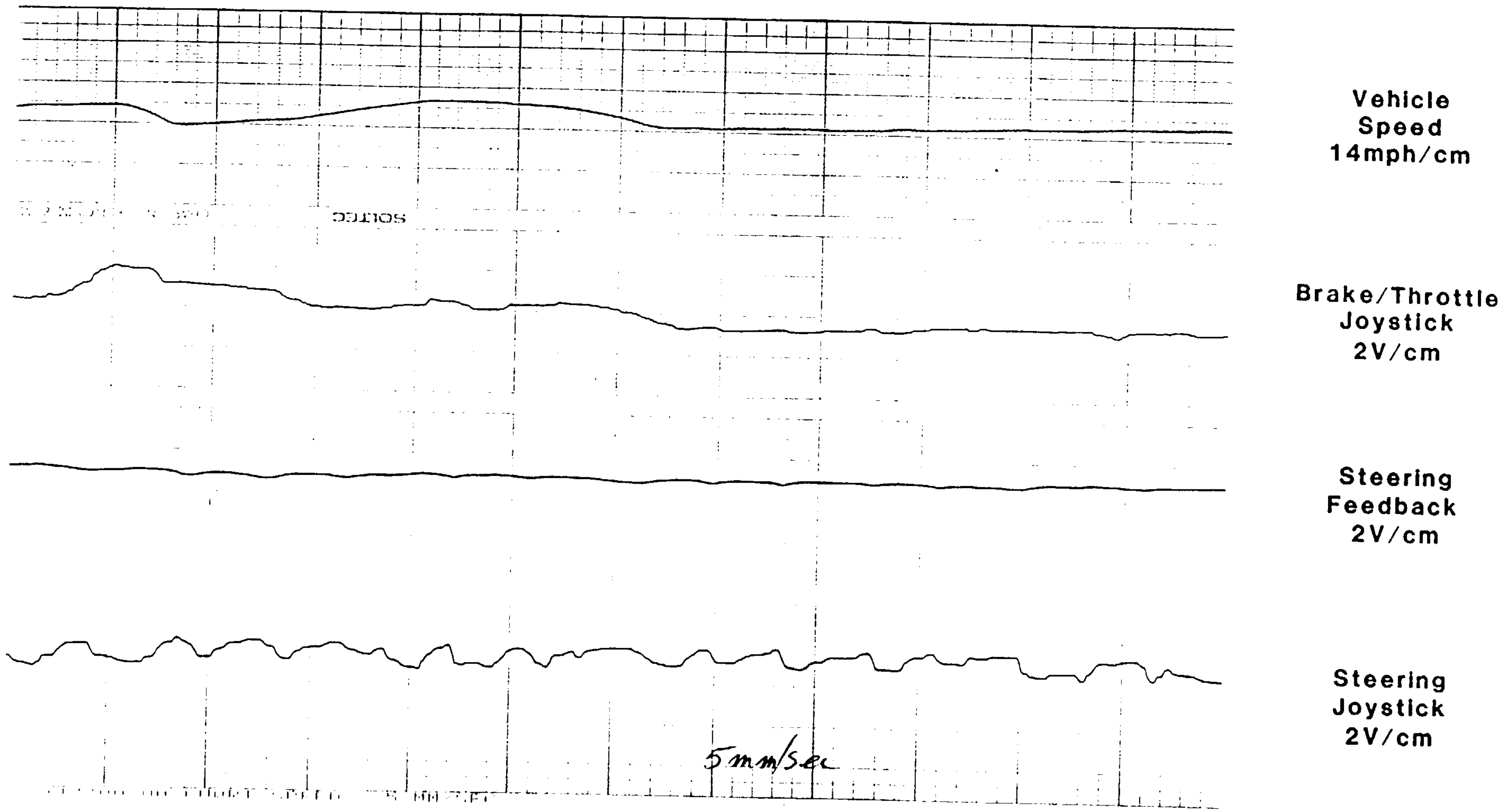


FIGURE C-139. VANCOUVER ROAD TEST - JULY 28, 1986 (A.M.)

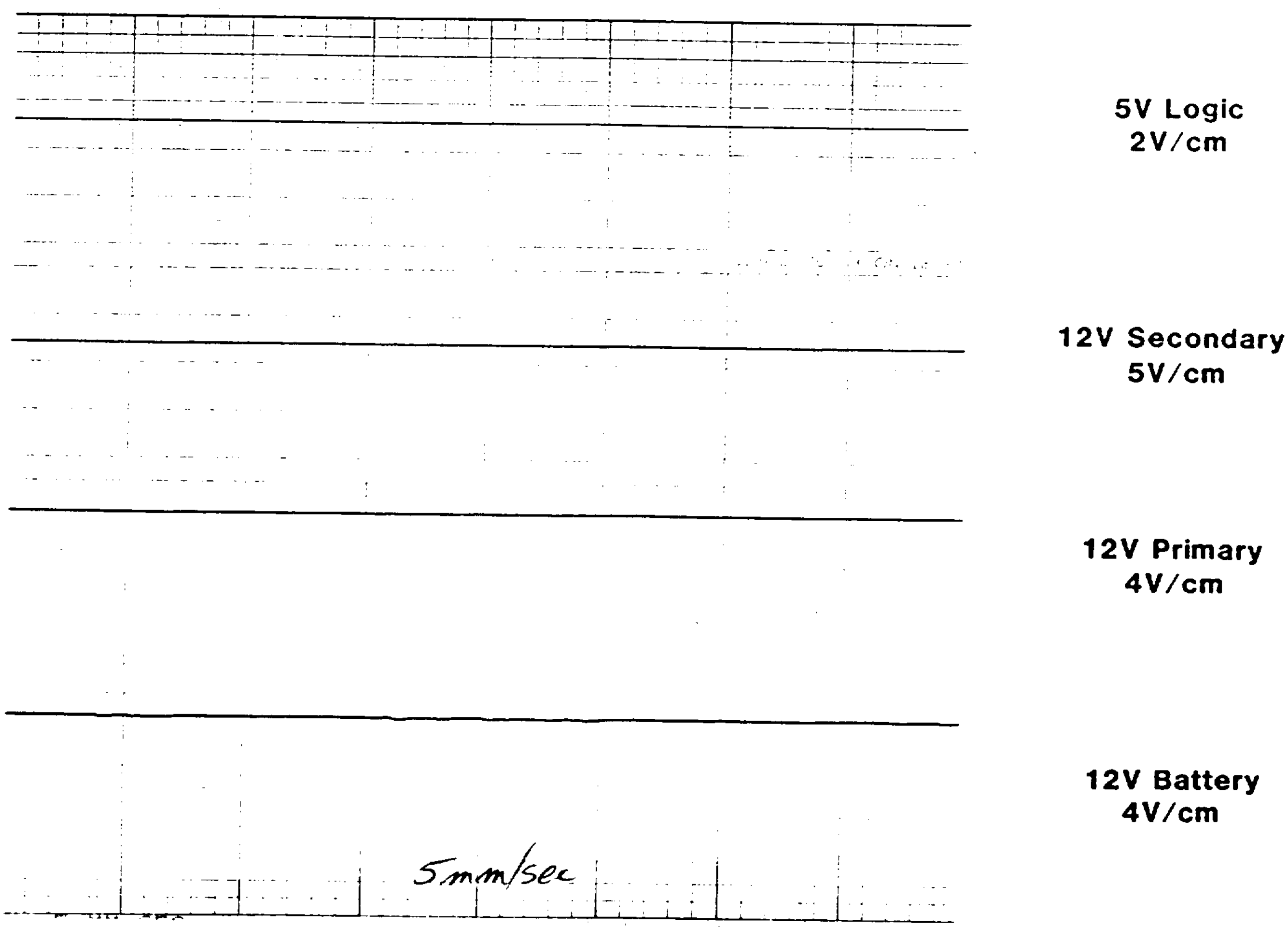


FIGURE C-140. VANCOUVER ROAD TEST - JULY 28, 1986 (A.M.)

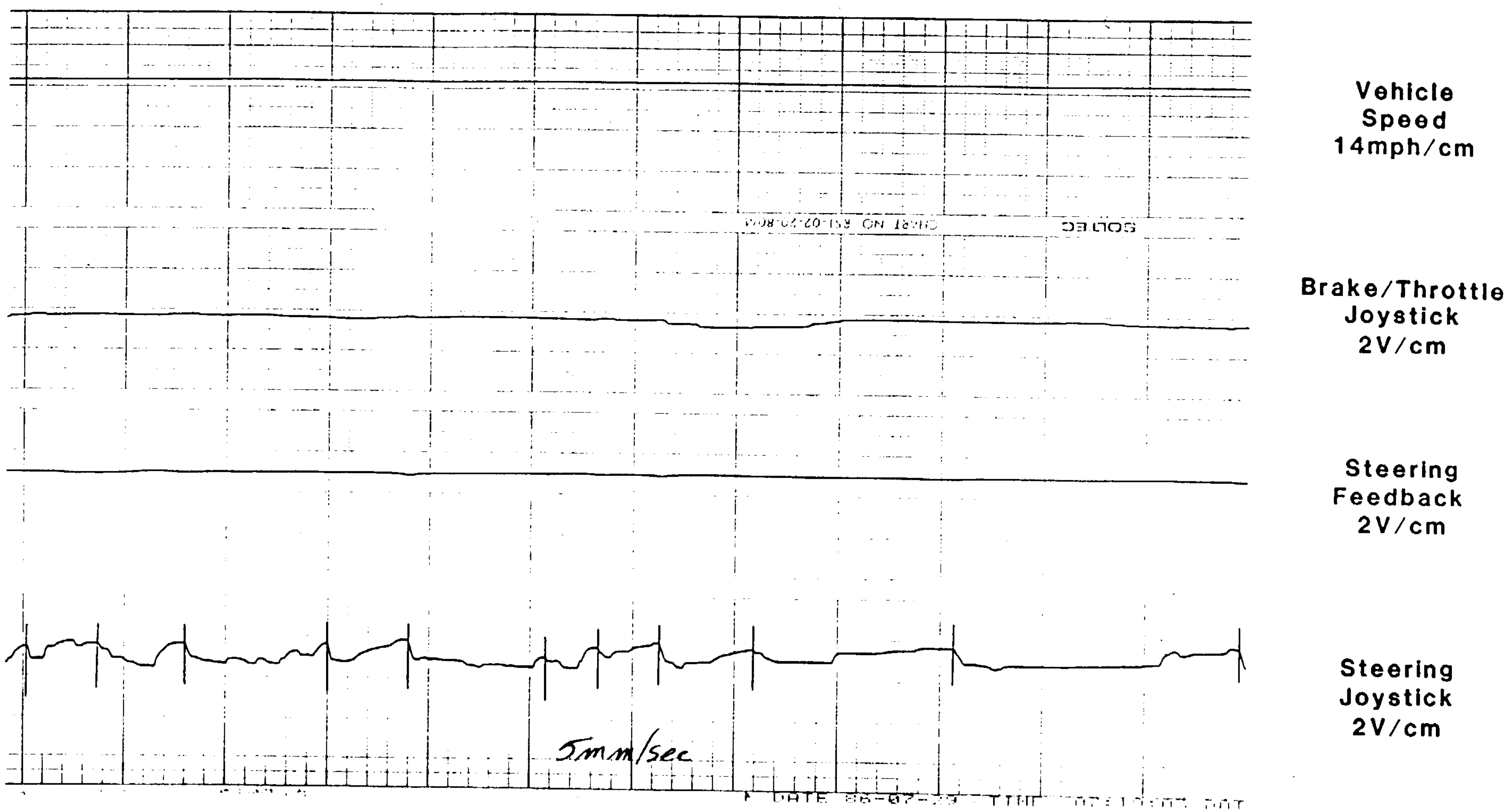


FIGURE C-141. VANCOUVER ROAD TEST - JULY 29, 1986 (A.M.)

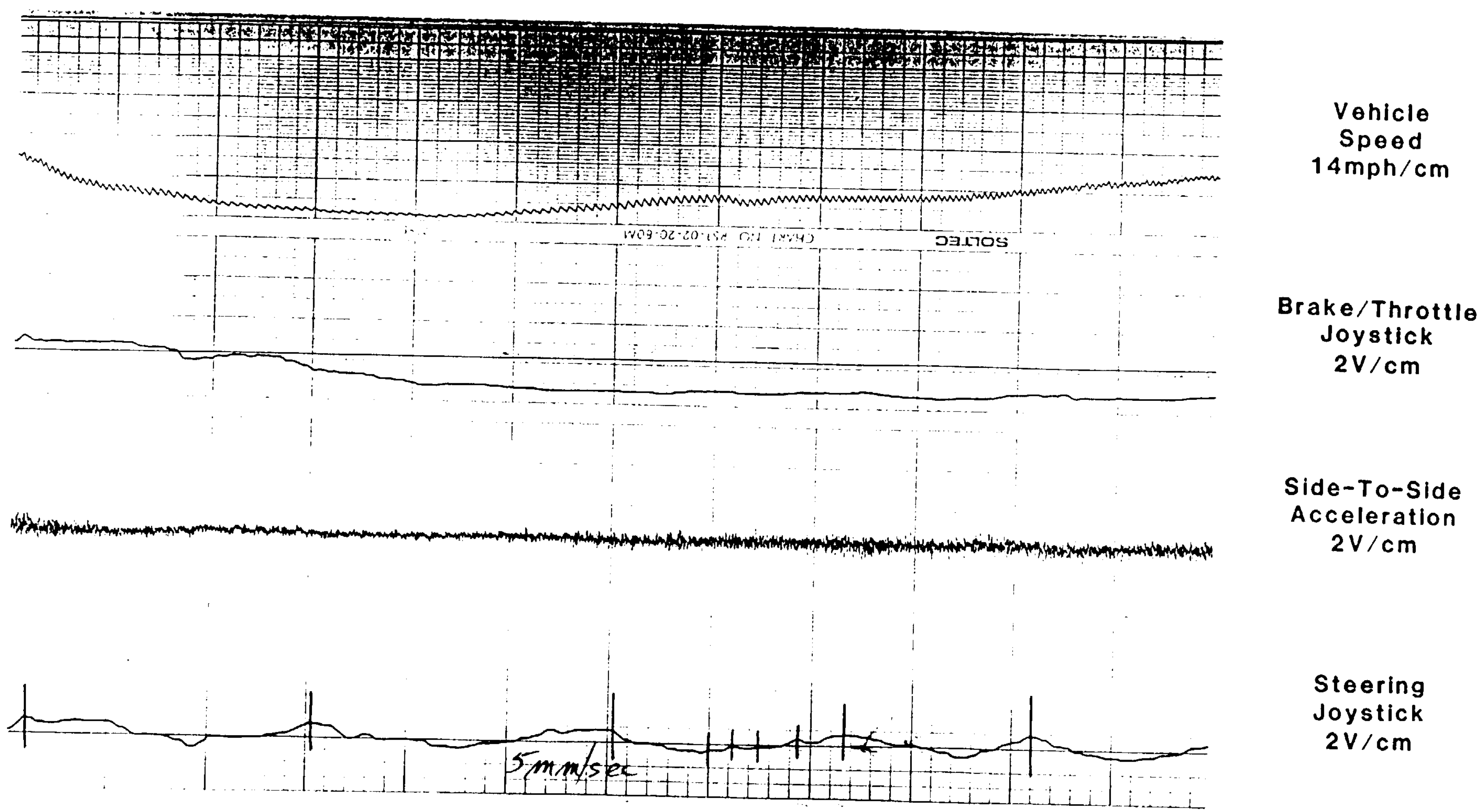


FIGURE C-142. HANDICAPPED DRIVER (FIRST DRIVING OPPORTUNITY)

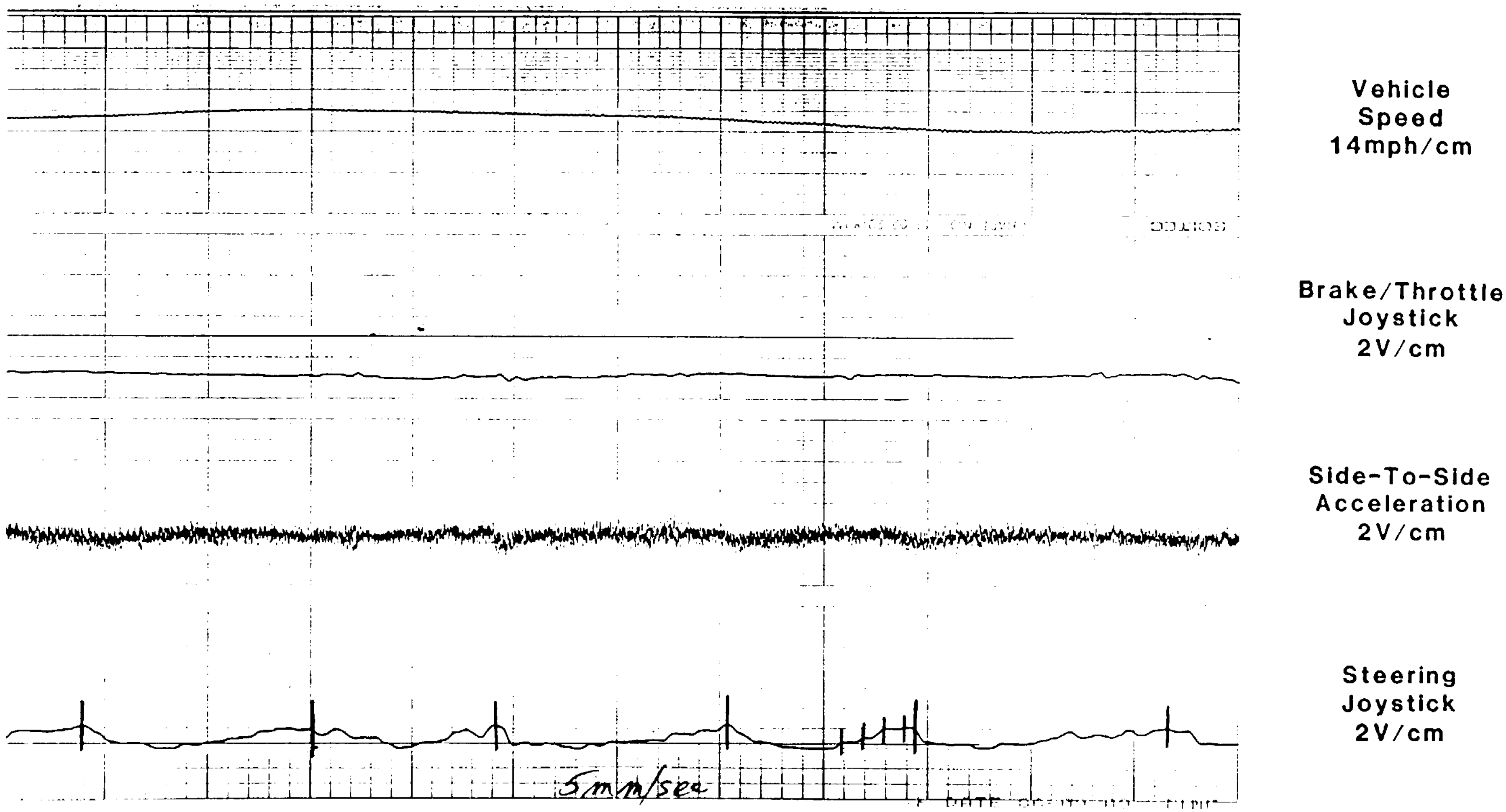


FIGURE C-143. HANDICAPPED DRIVER (AFTER DRIVING ABOUT 15 MINUTES)

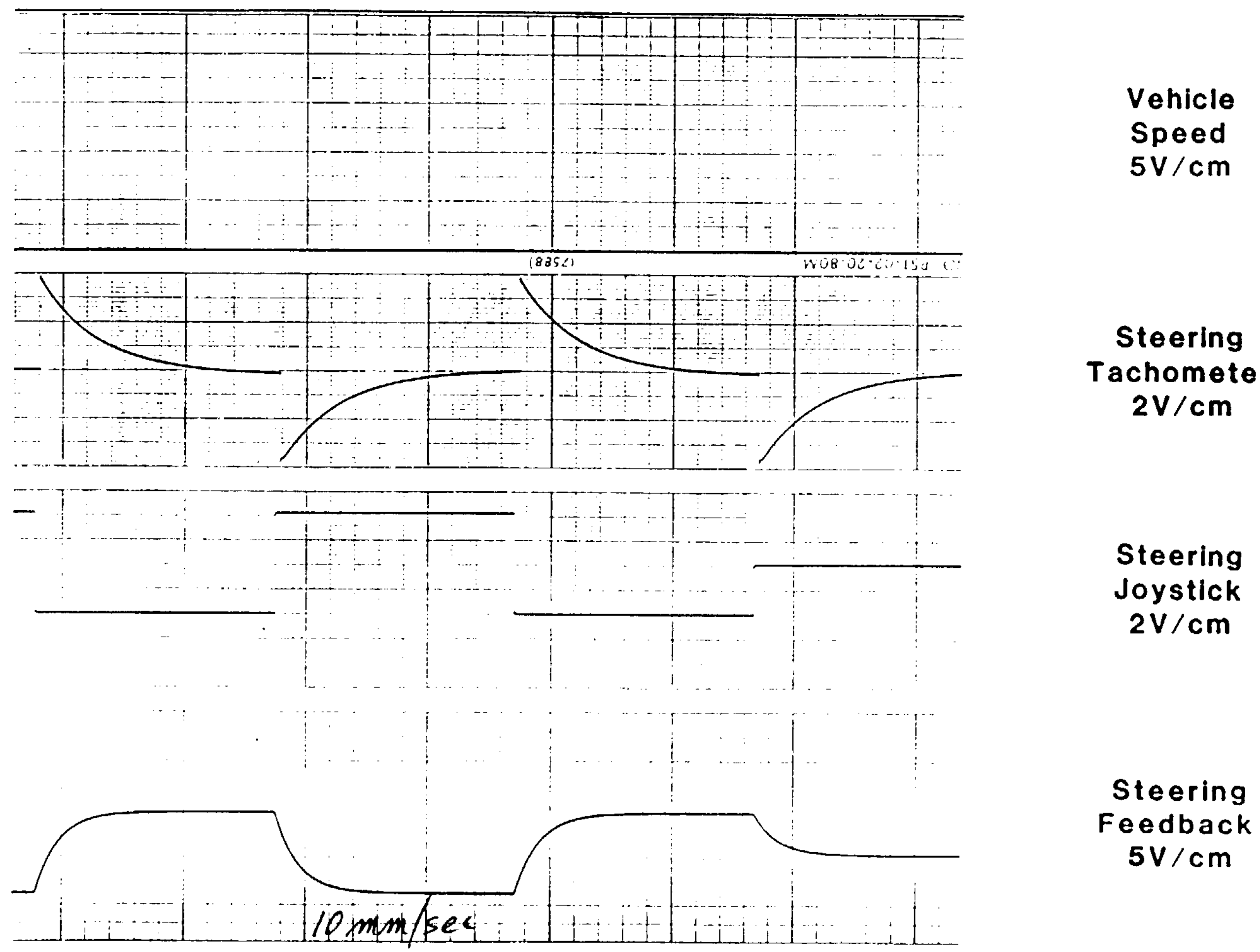


FIGURE C-144. SERVO ELECTRONICS TEST INPUTS (12V POWER)(SPEED LOW)

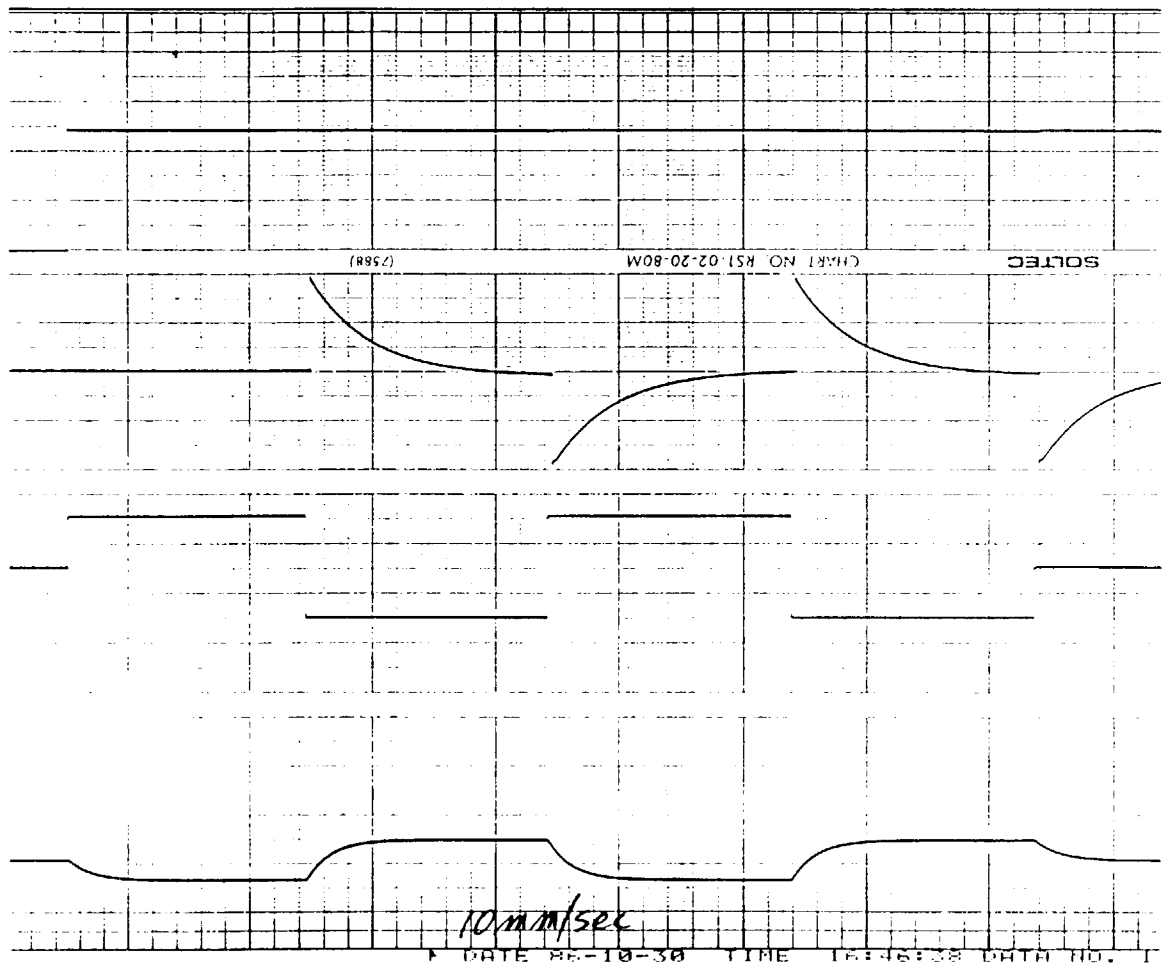


FIGURE C-145. SERVO ELECTRONICS TEST INPUTS (12V POWER)(SPEED HIGH)

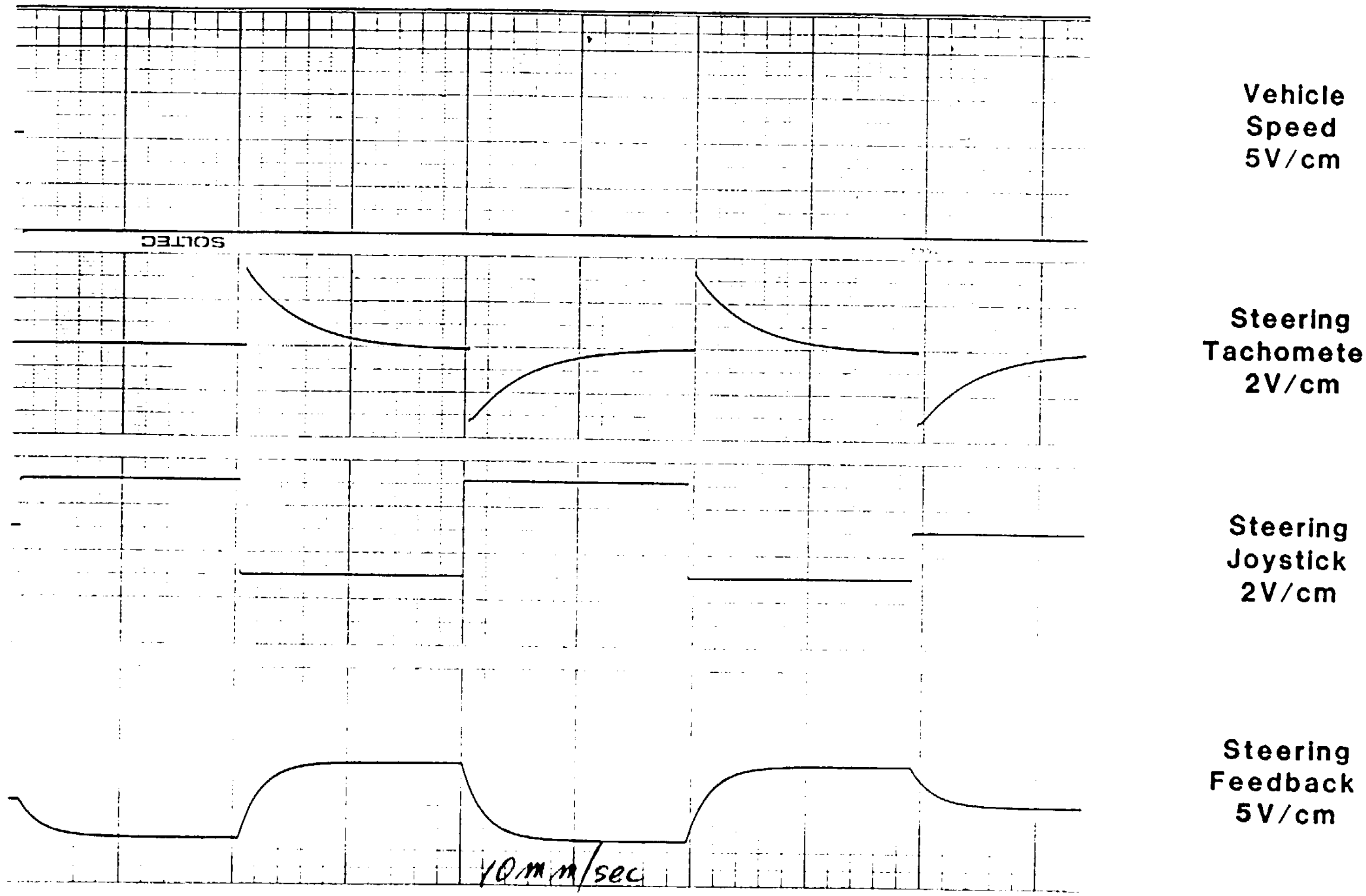


FIGURE C-146. SERVO ELECTRONICS TEST INPUTS (10.6V POWER)(SPEED LOW)

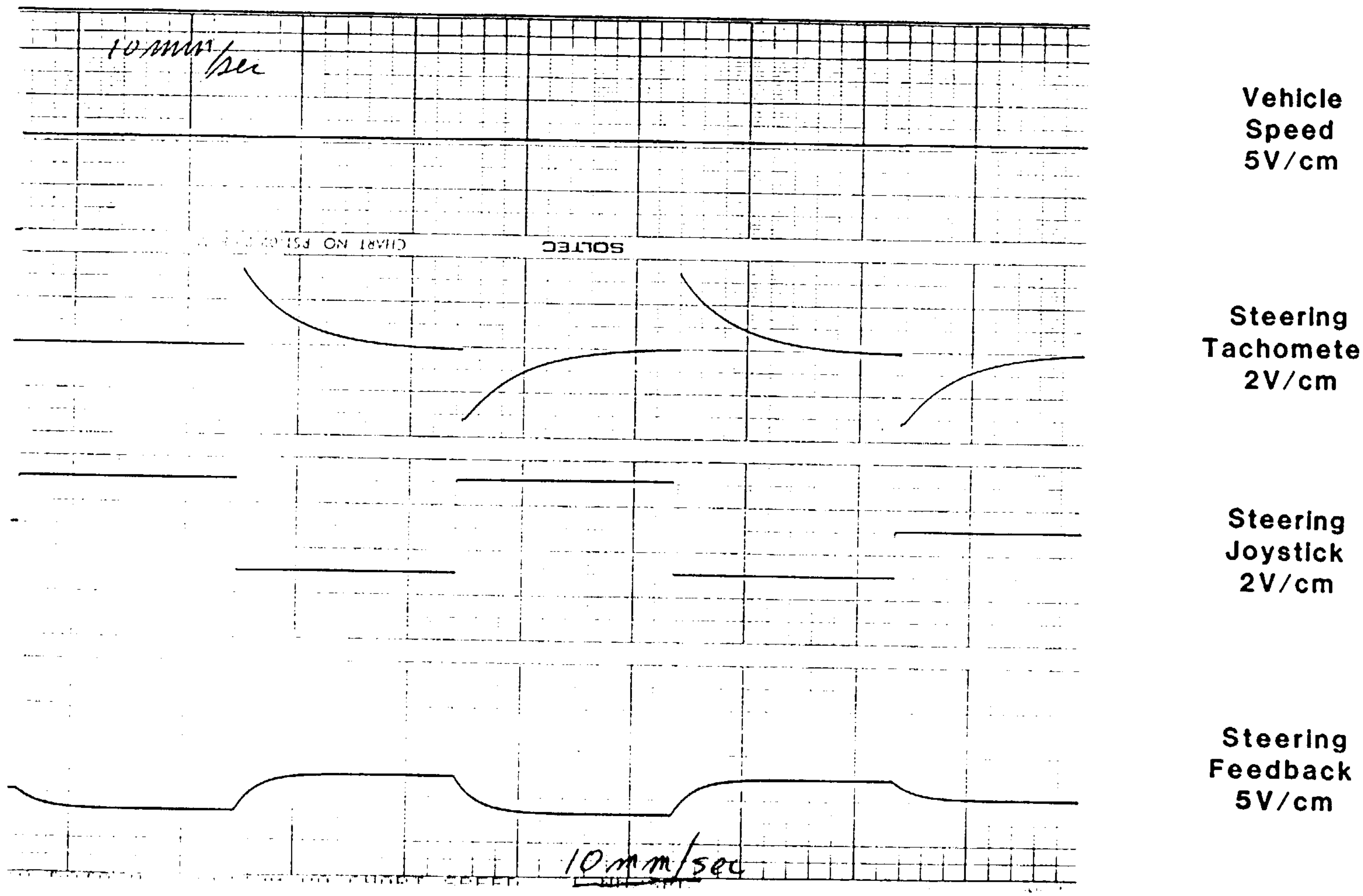


FIGURE C-147. SERVO ELECTRONICS TEST INPUTS (10.6V POWER)(SPEED HIGH)

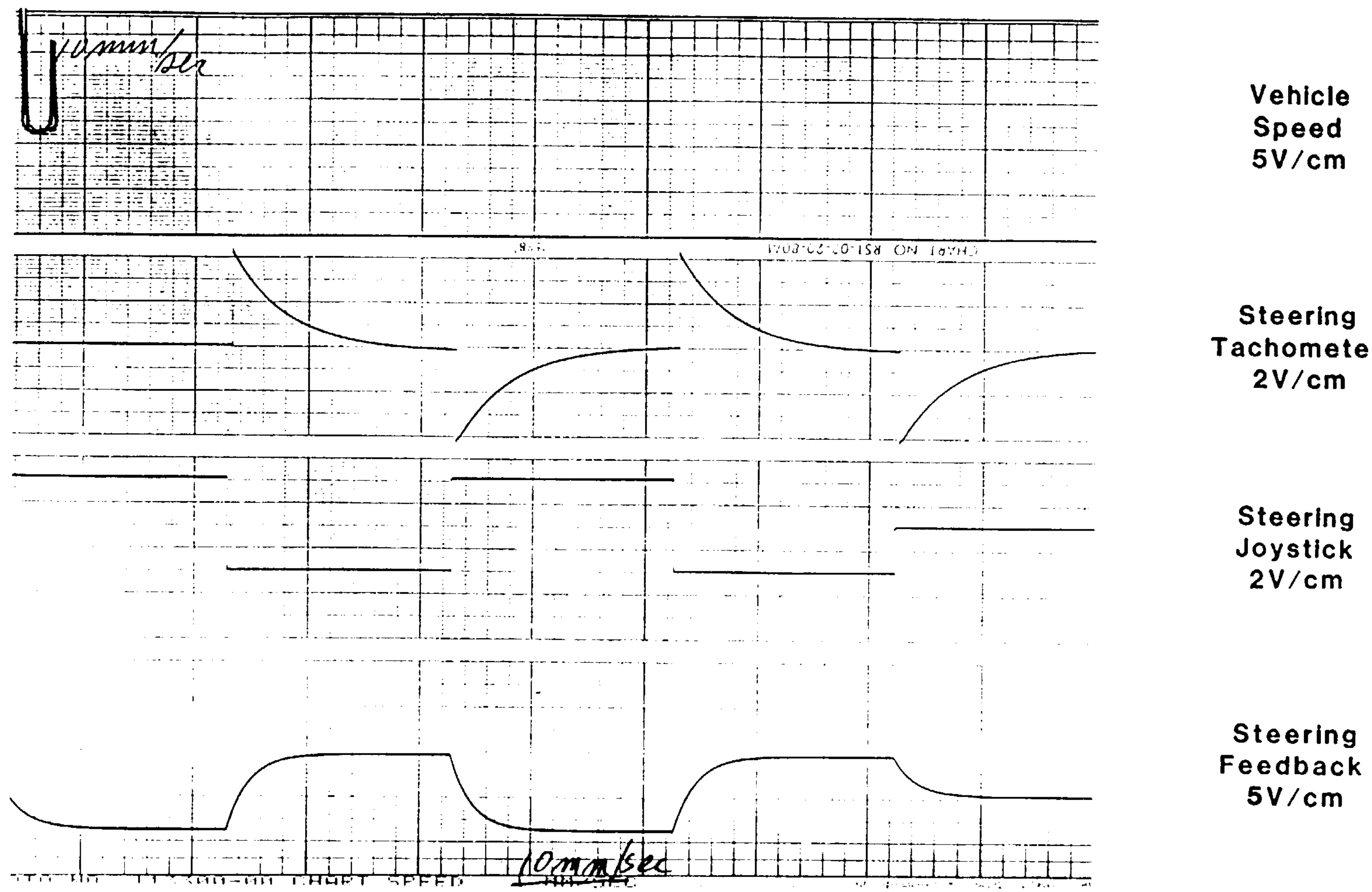


FIGURE C-148. SERVO ELECTRONICS TEST INPUTS (13.4V POWER)(SPEED LOW)

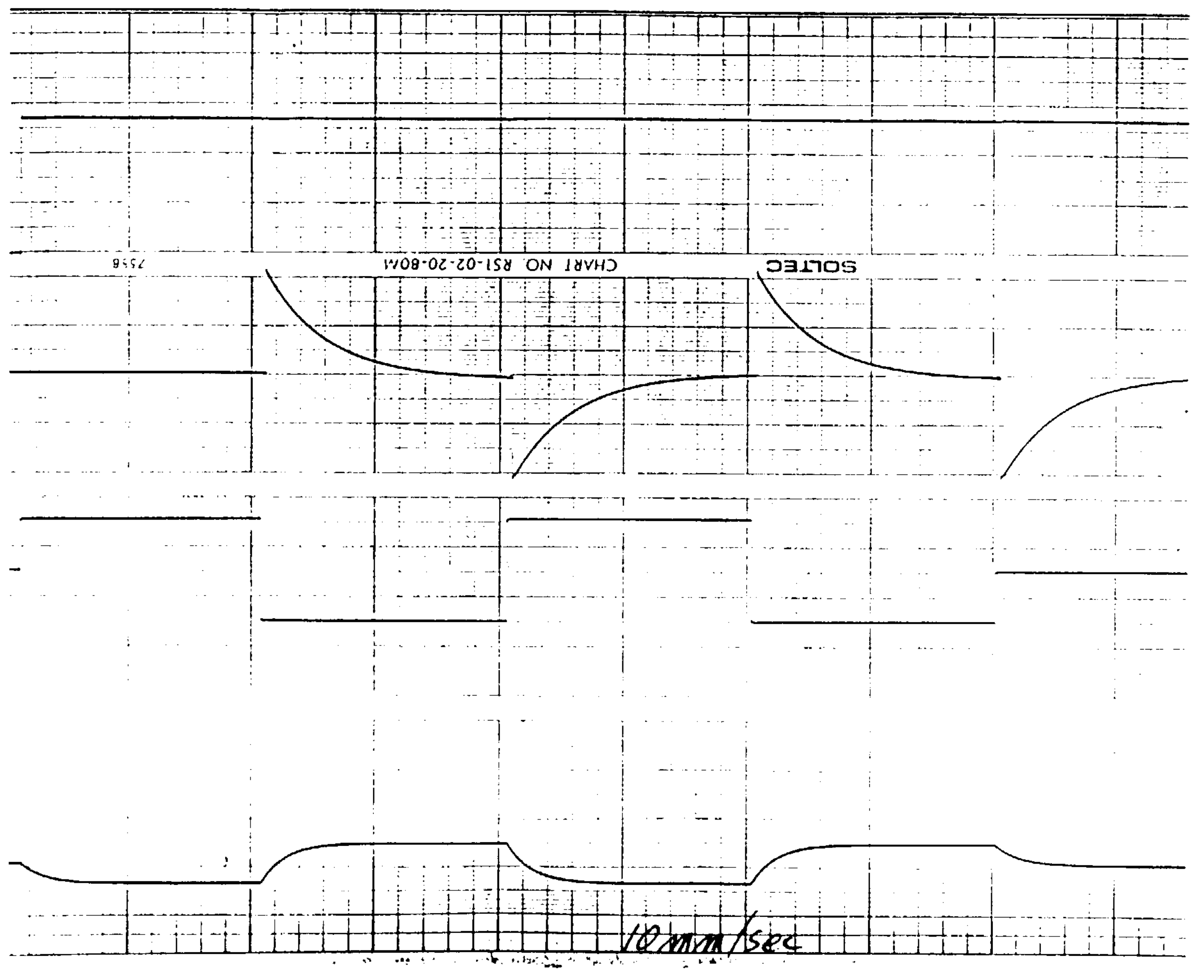


FIGURE C-149. SERVO ELECTRONICS TEST INPUTS (13.4V POWER)(SPEED HIGH)

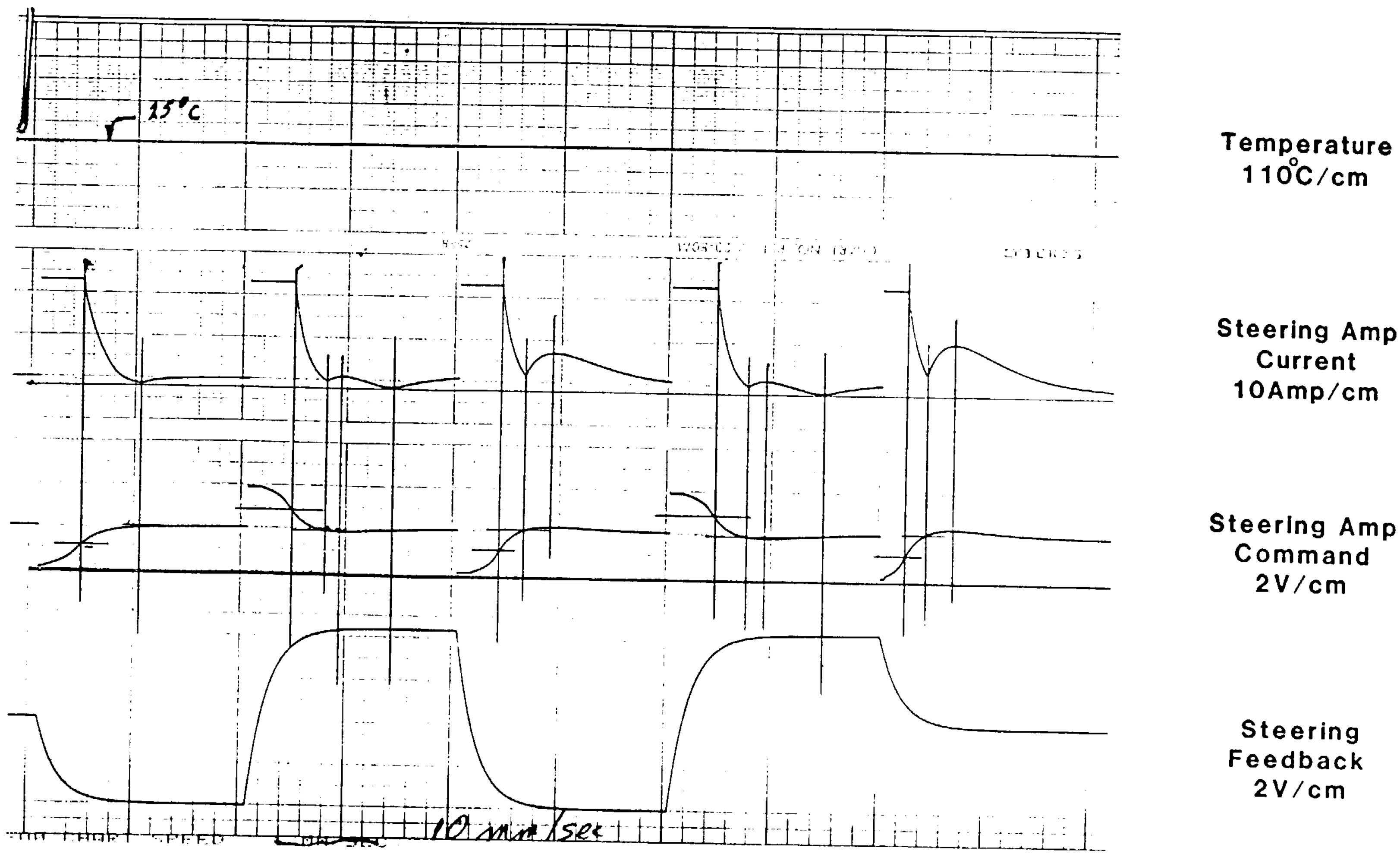


FIGURE C-150. STEERING SERVO TEMPERATURE CYCLE (INITIAL AT 25°C, 12V POWER)

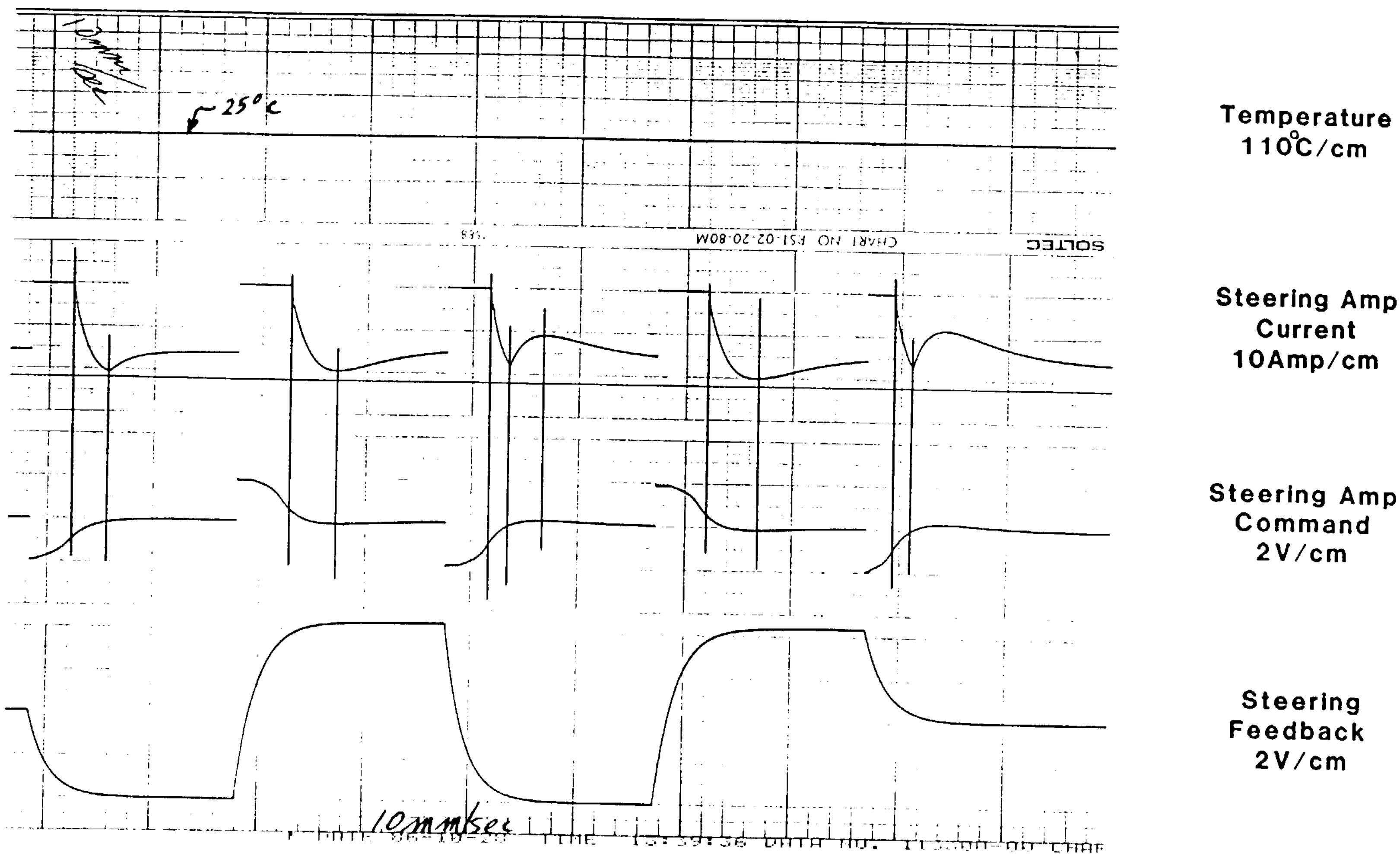


FIGURE C-151. STEERING SERVO TEMPERATURE CYCLE (INITIAL AT 25°C, 10.6V POWER)

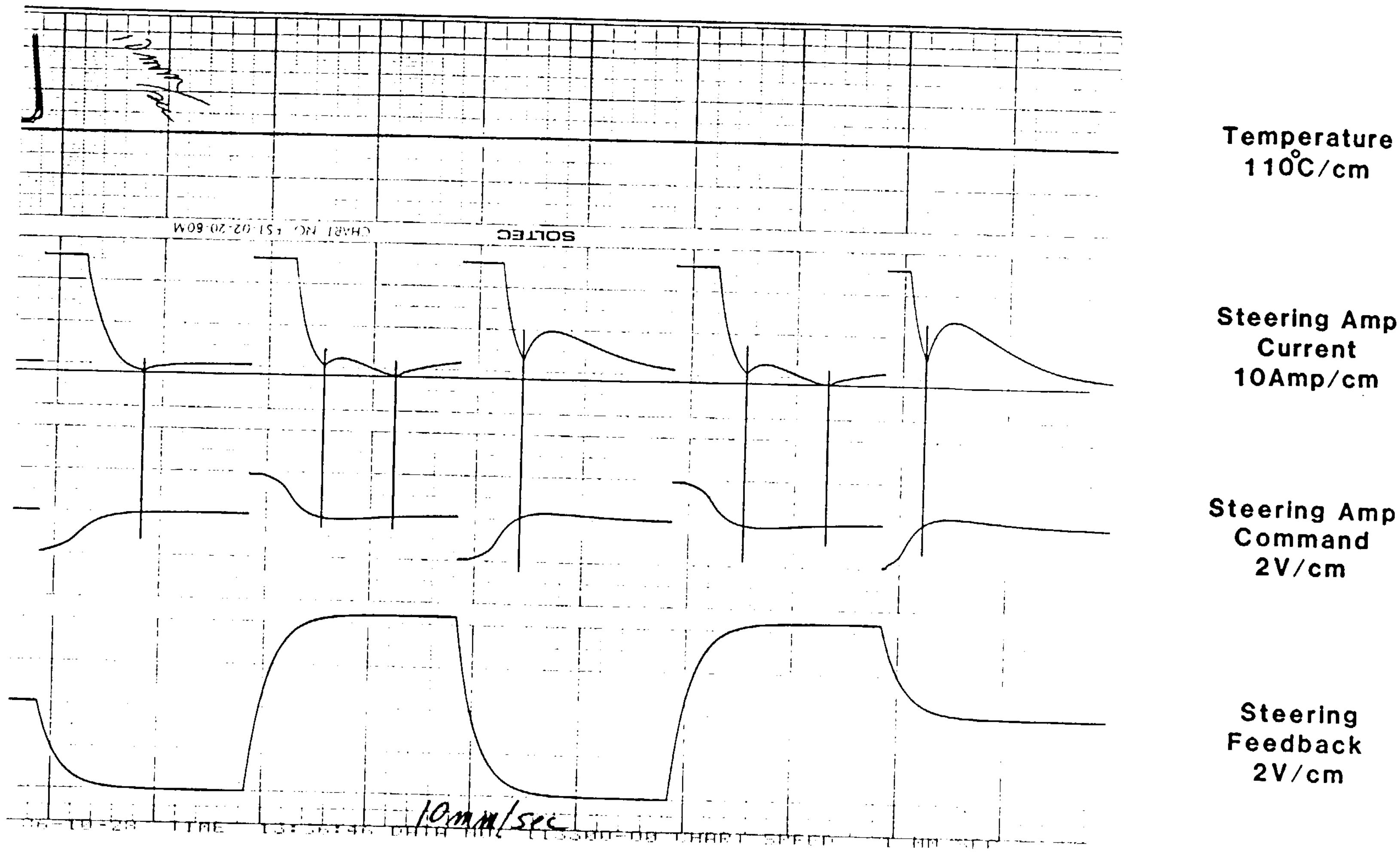


FIGURE C-152. STEERING SERVO TEMPERATURE CYCLE (INITIAL AT 25°C, 13.4V POWER)

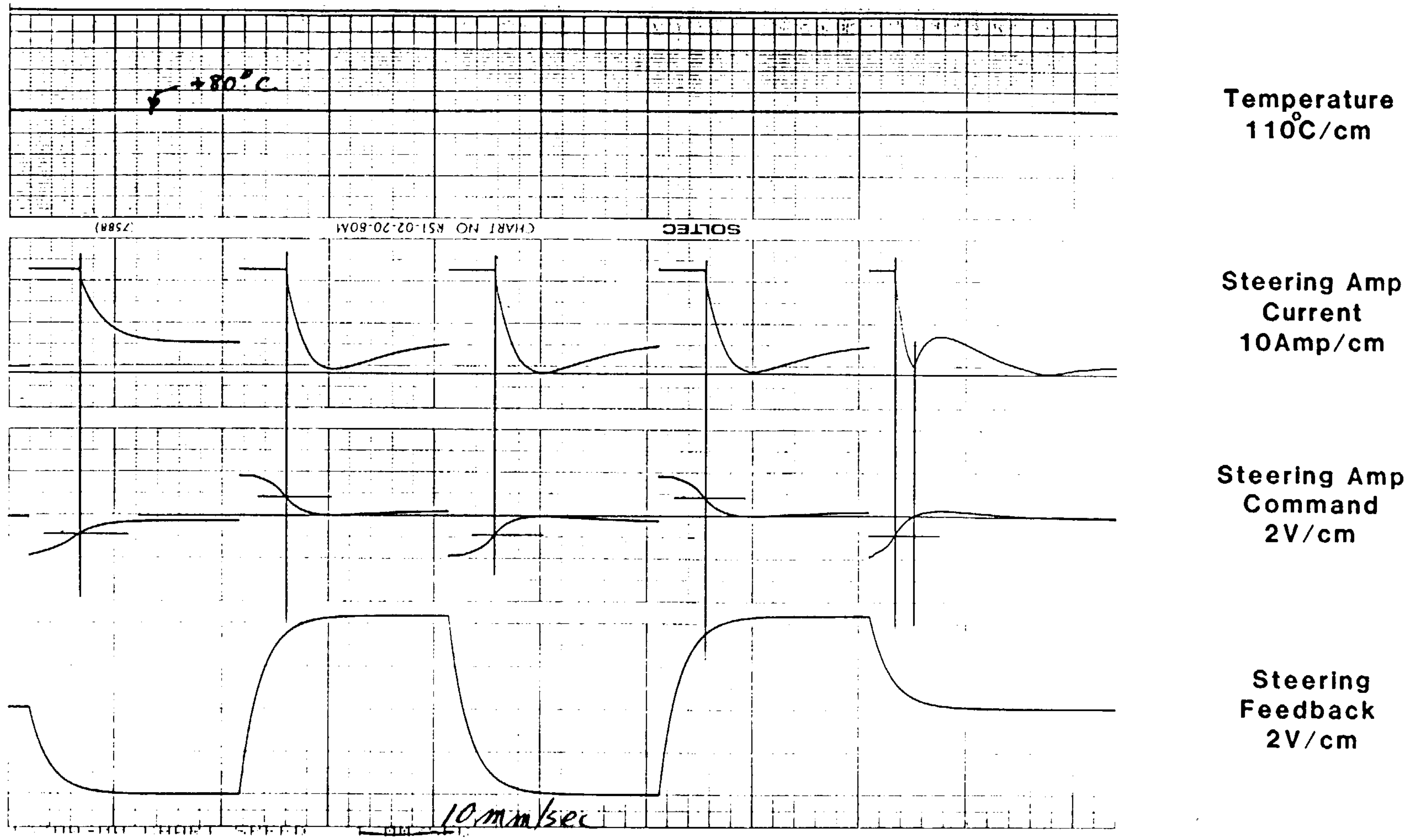


FIGURE C-153. STEERING SERVO TEMPERATURE CYCLE (+80°C, 12V POWER)

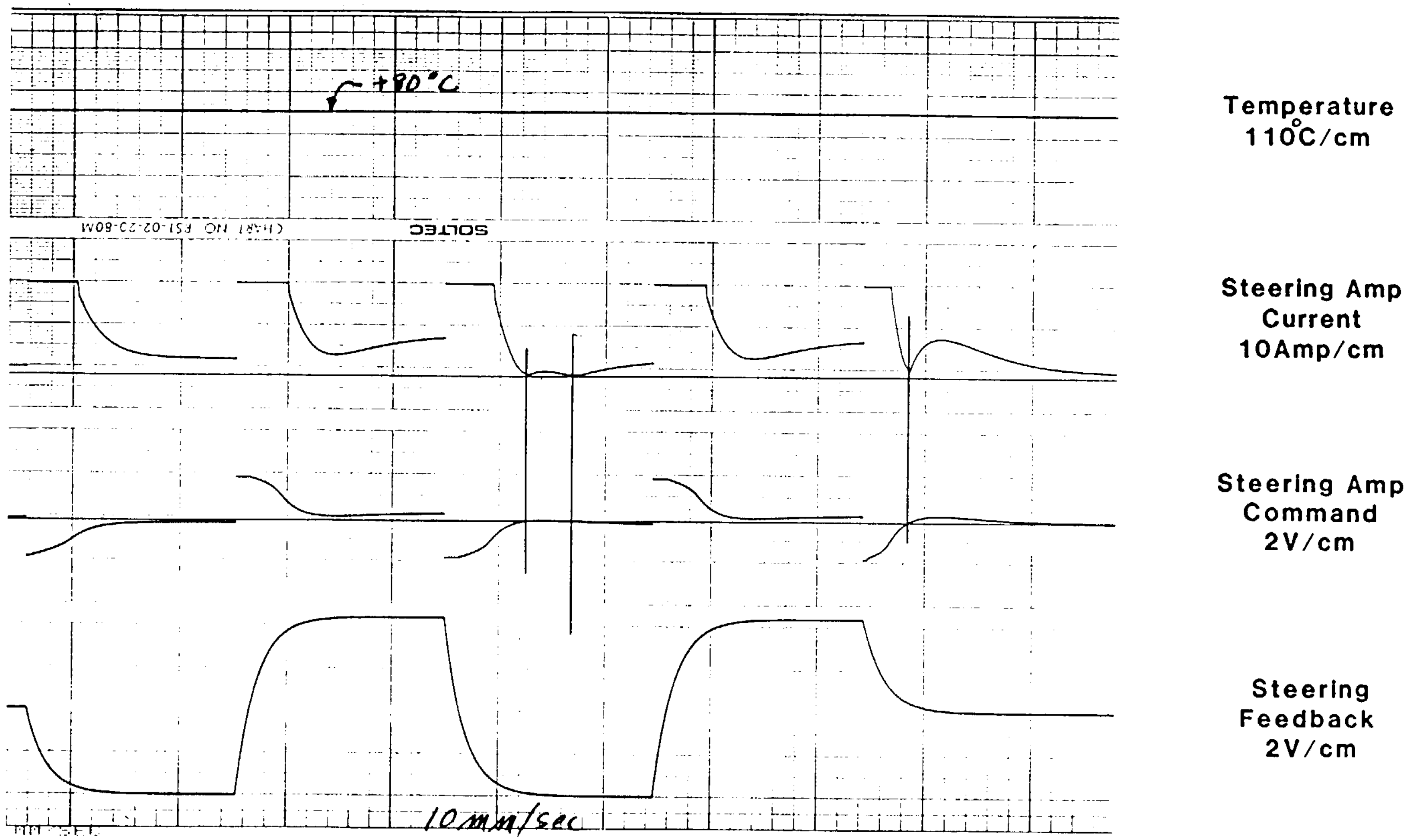


FIGURE C-154. STEERING SERVO TEMPERATURE CYCLE (+80°C, 10.6V POWER)

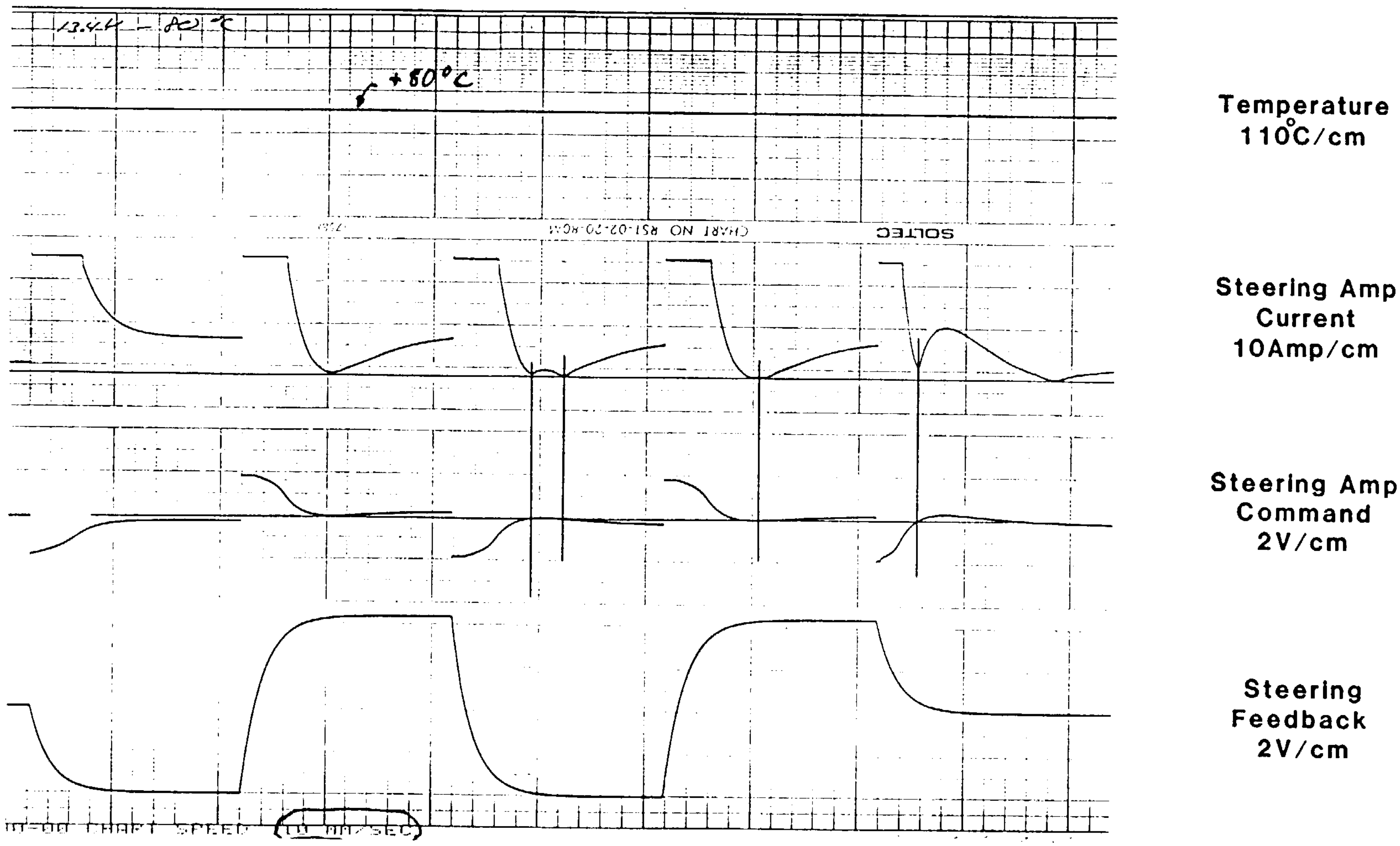


FIGURE C-155. STEERING SERVO TEMPERATURE CYCLE (+80°C, 13.4V POWER)

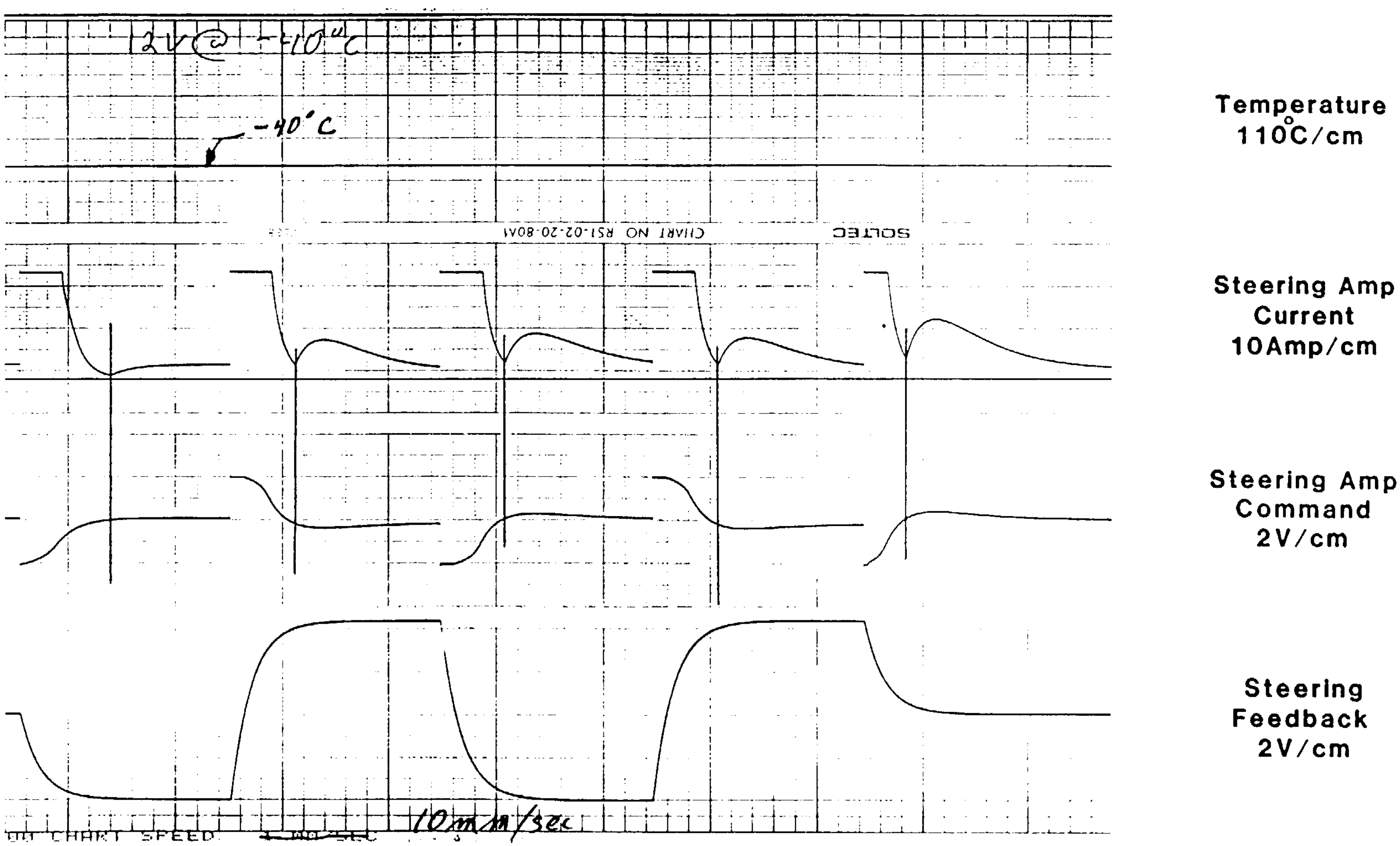


FIGURE C-156. STEERING SERVO TEMPERATURE CYCLE (-40°C, 12V POWER)

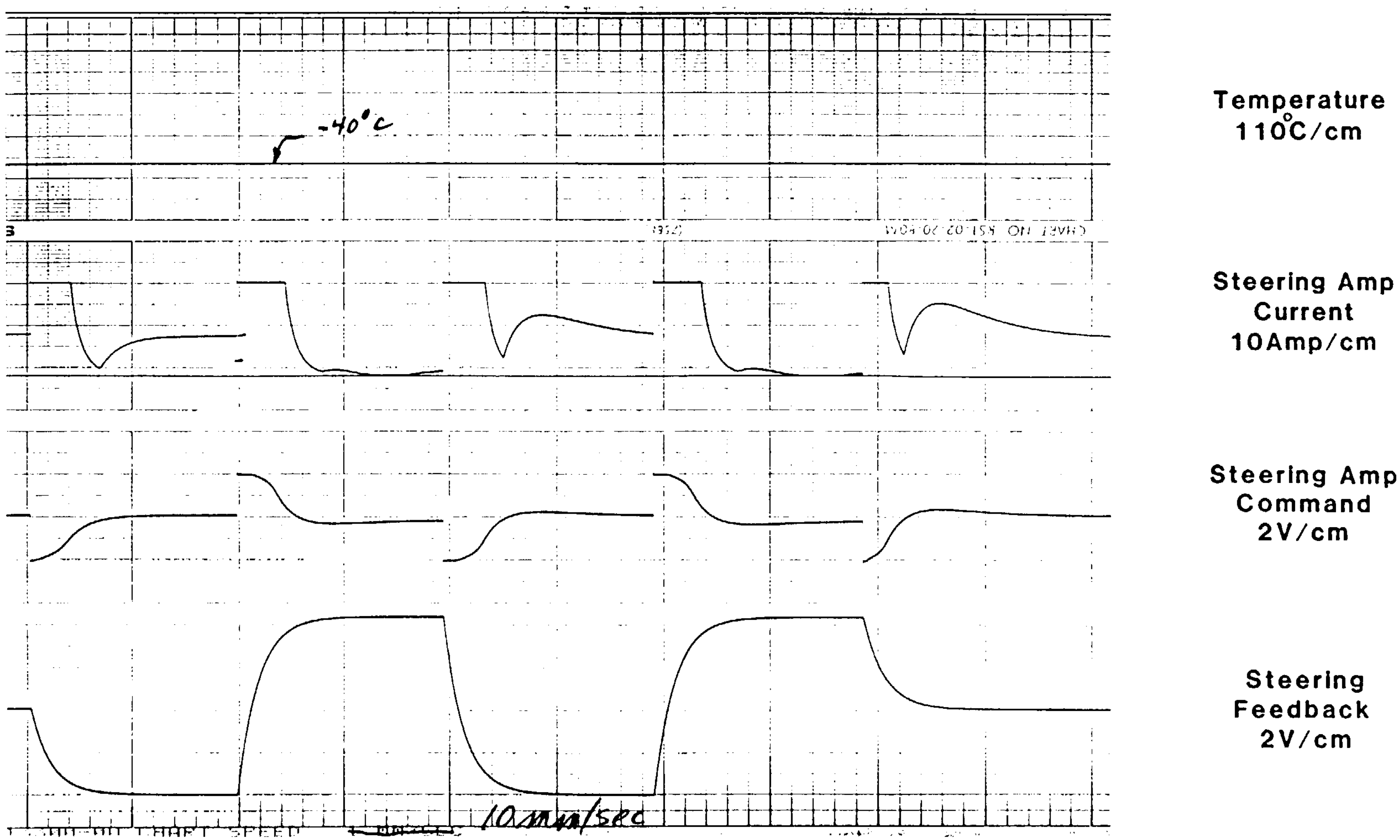


FIGURE C-157. STEERING SERVO TEMPERATURE CYCLE (-40°C, 10.6V POWER)

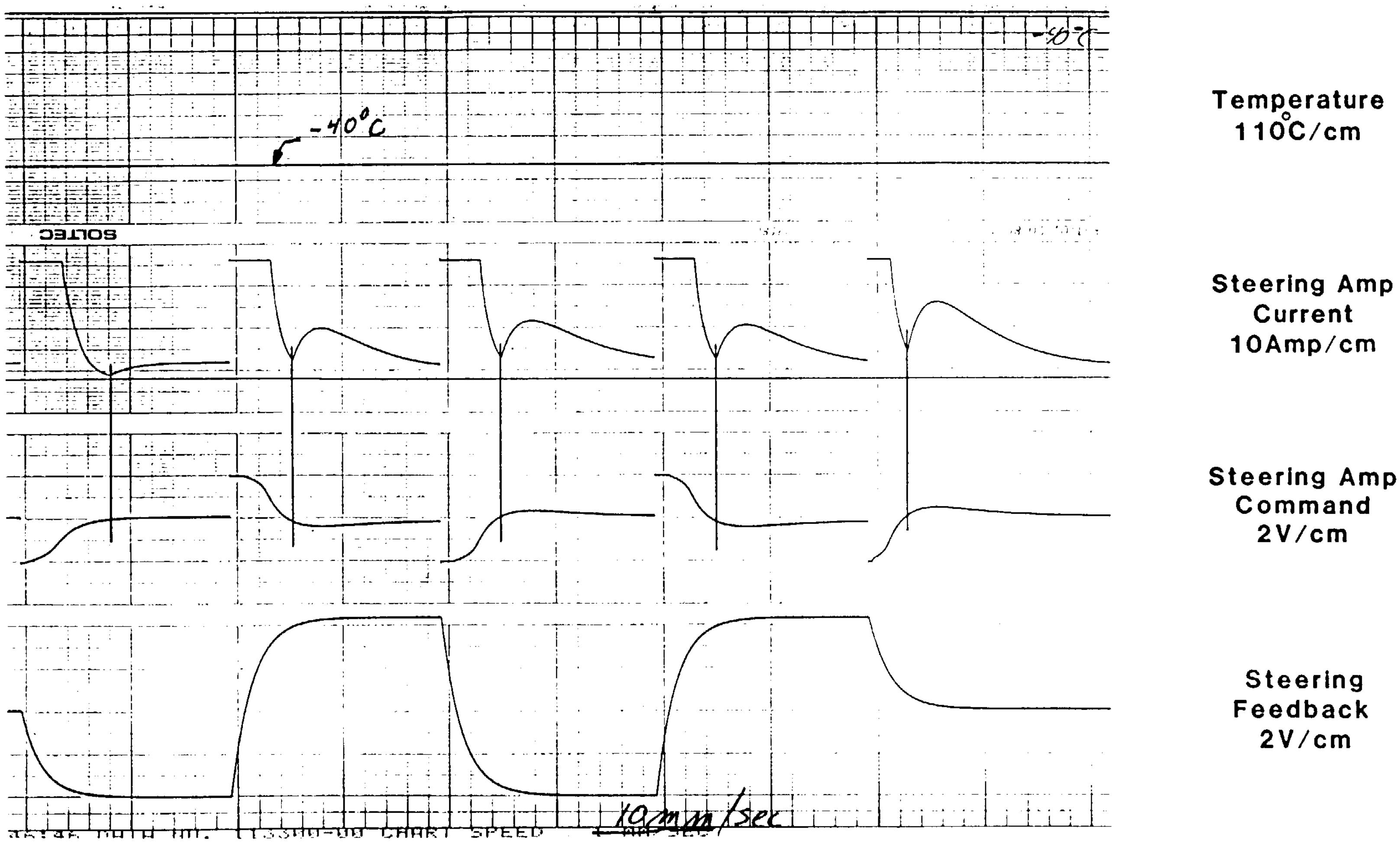


FIGURE C-158. STEERING SERVO TEMPERATURE CYCLE (-40°C, 13.4V POWER)

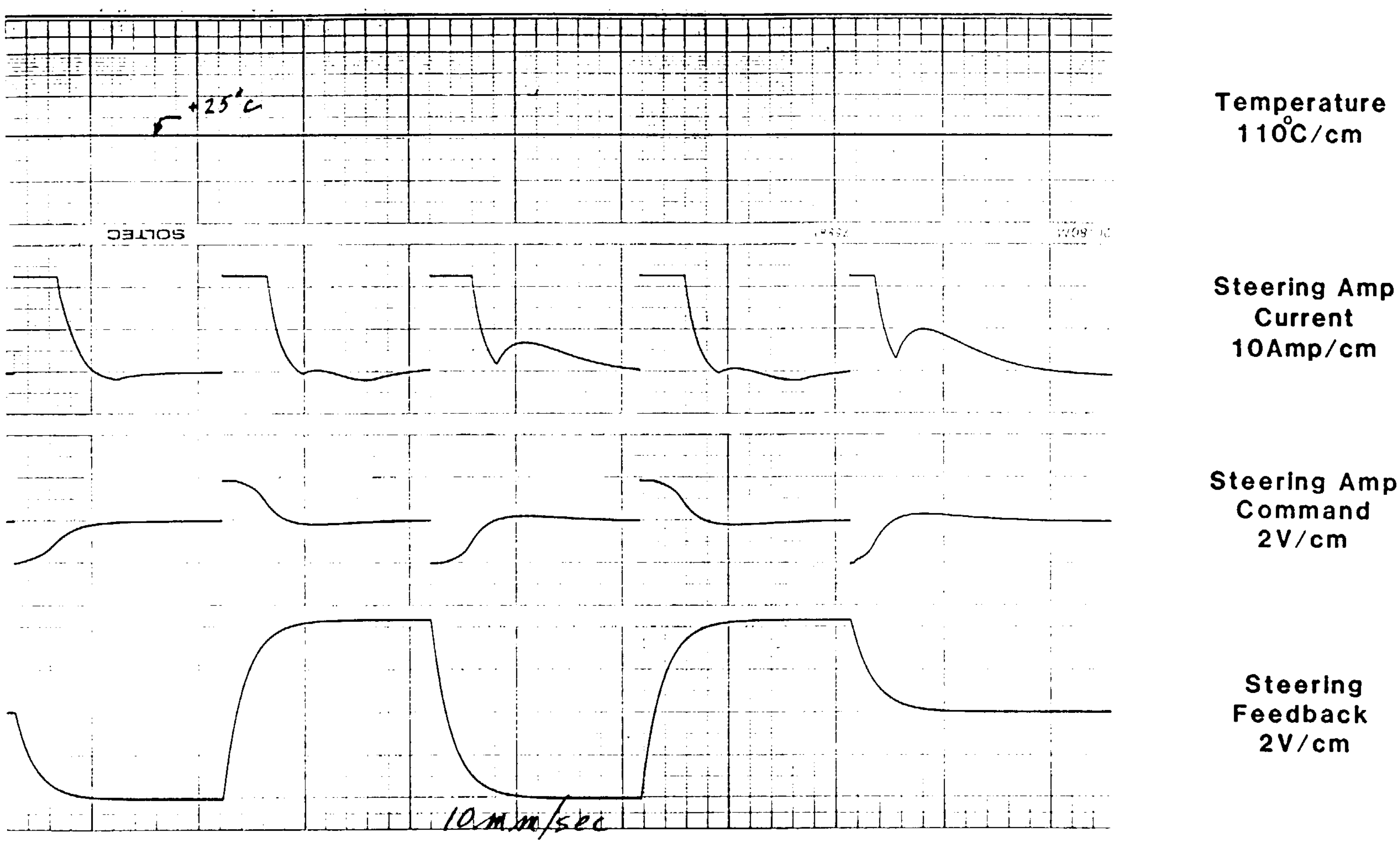


FIGURE C-159. STEERING SERVO TEMPERATURE CYCLE (FINAL AT +25°C, 12V POWER)

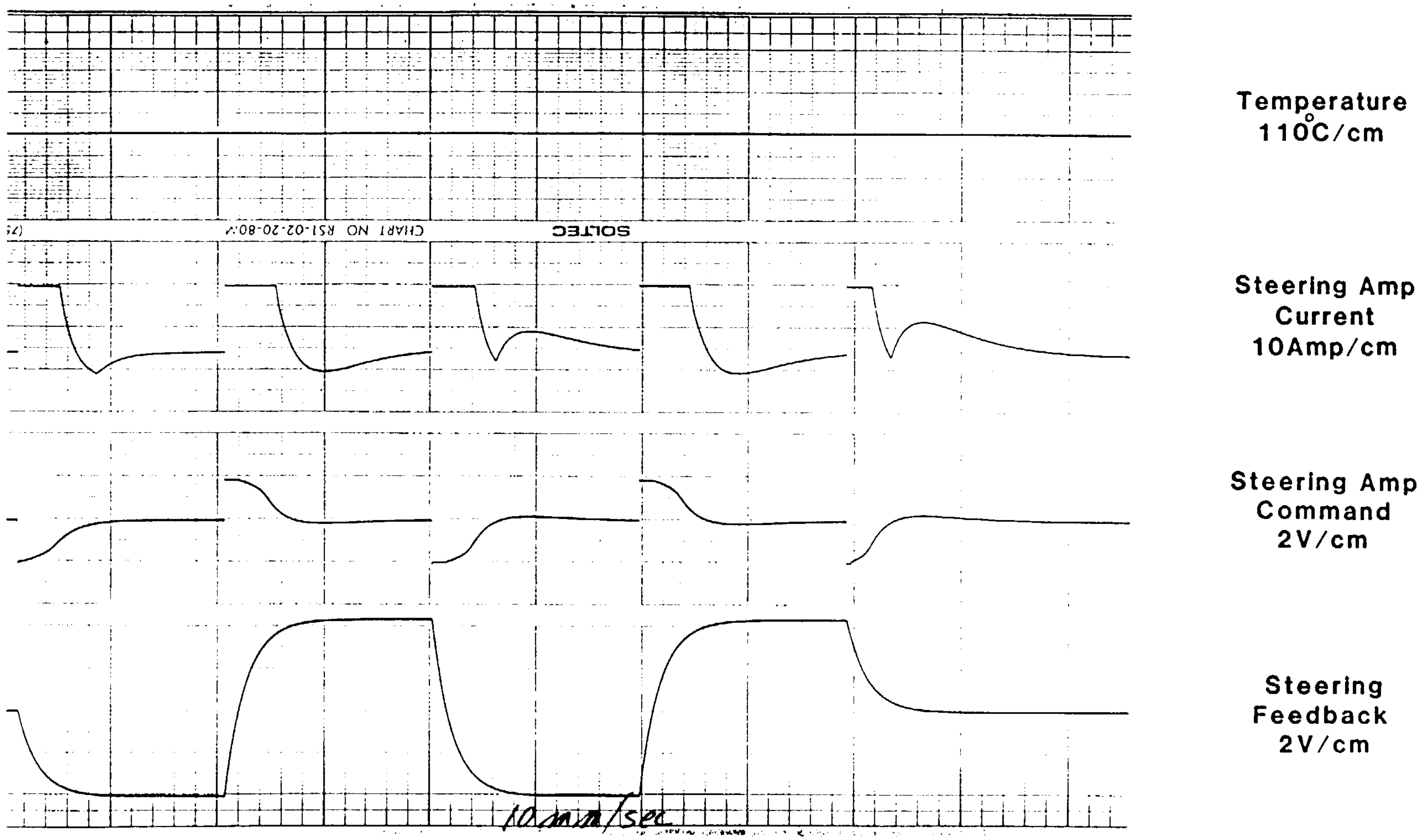


FIGURE C-160. STEERING SERVO TEMPERATURE CYCLE (FINAL AT +25°C, 10.6V POWER)

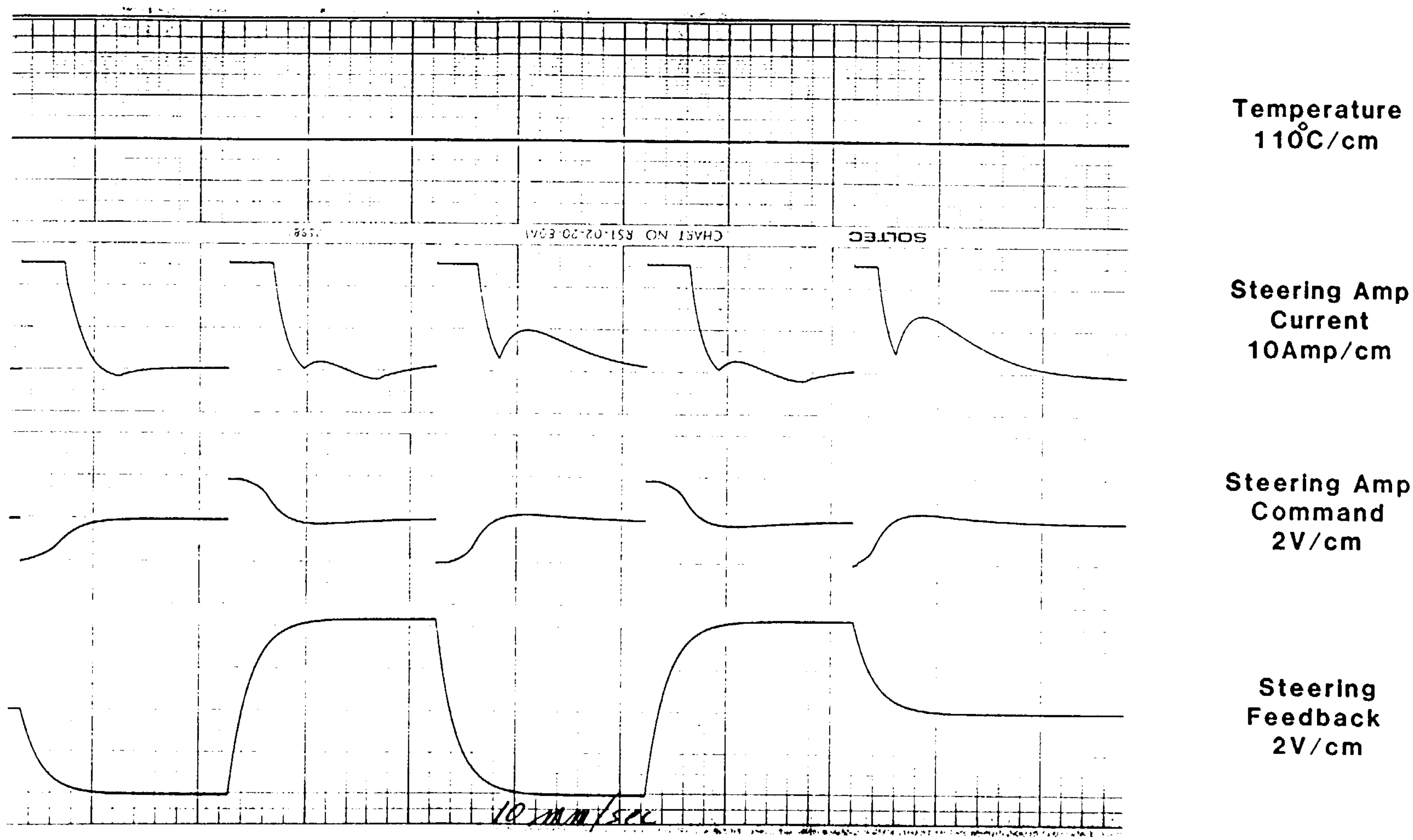


FIGURE C-161. STEERING SERVO TEMPERATURE CYCLE (FINAL AT +25°C, 13.4V POWER)

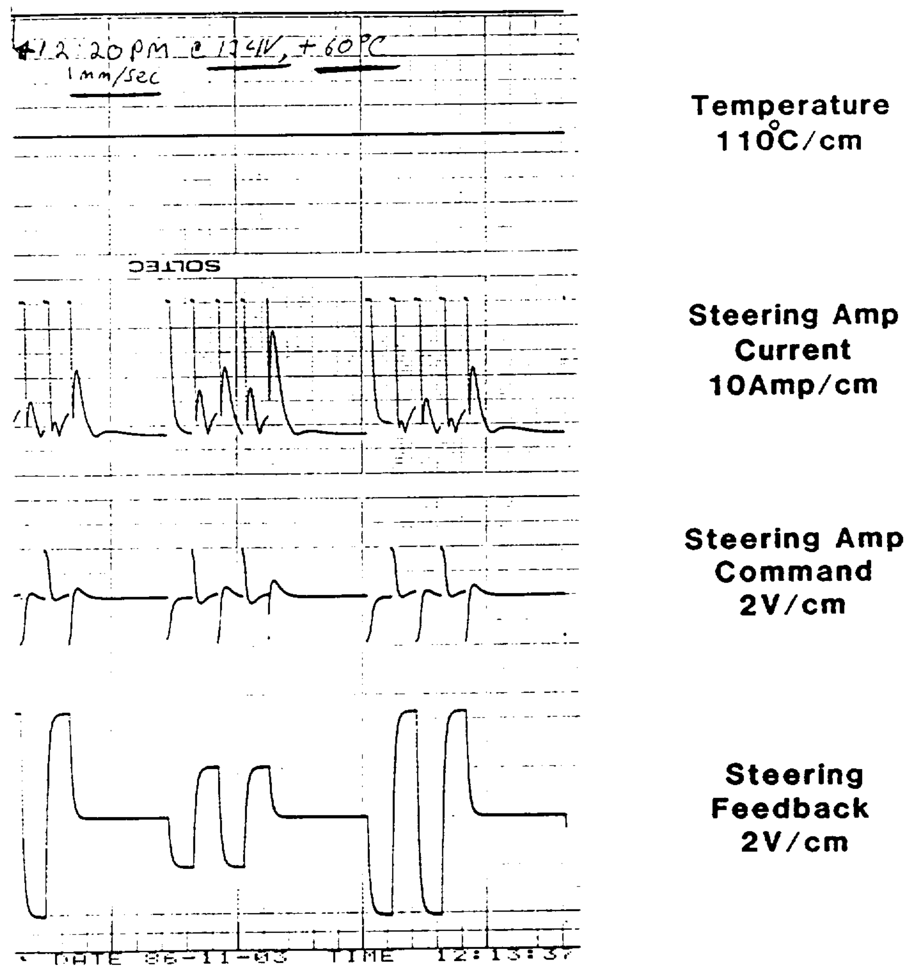
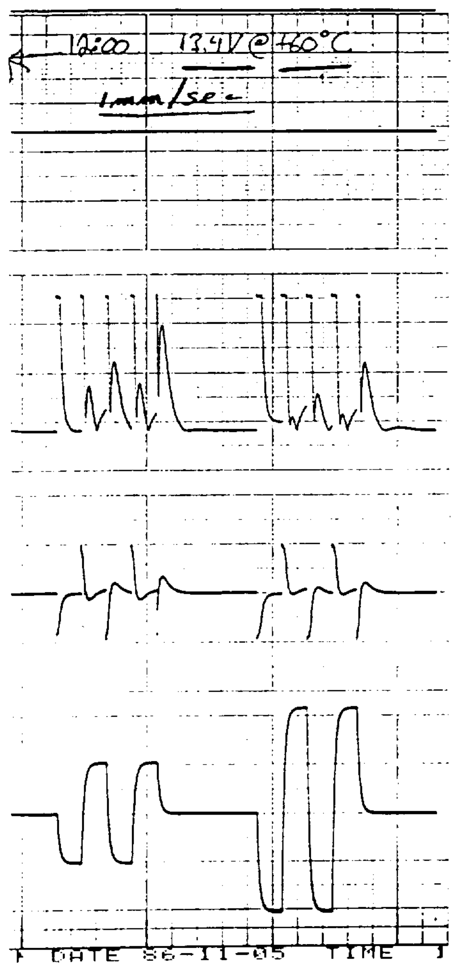


FIGURE C-162. STEERING SERVO TEMPERATURE SOAK (START-UP)



Temperature
110°C/cm

Steering Amp
Current
10Amp/cm

Steering Amp
Command
2V/cm

Steering
Feedback
2V/cm

FIGURE C-163. STEERING SERVO TEMPERATURE SOAK (BEFORE COMPONENT FAILURE)

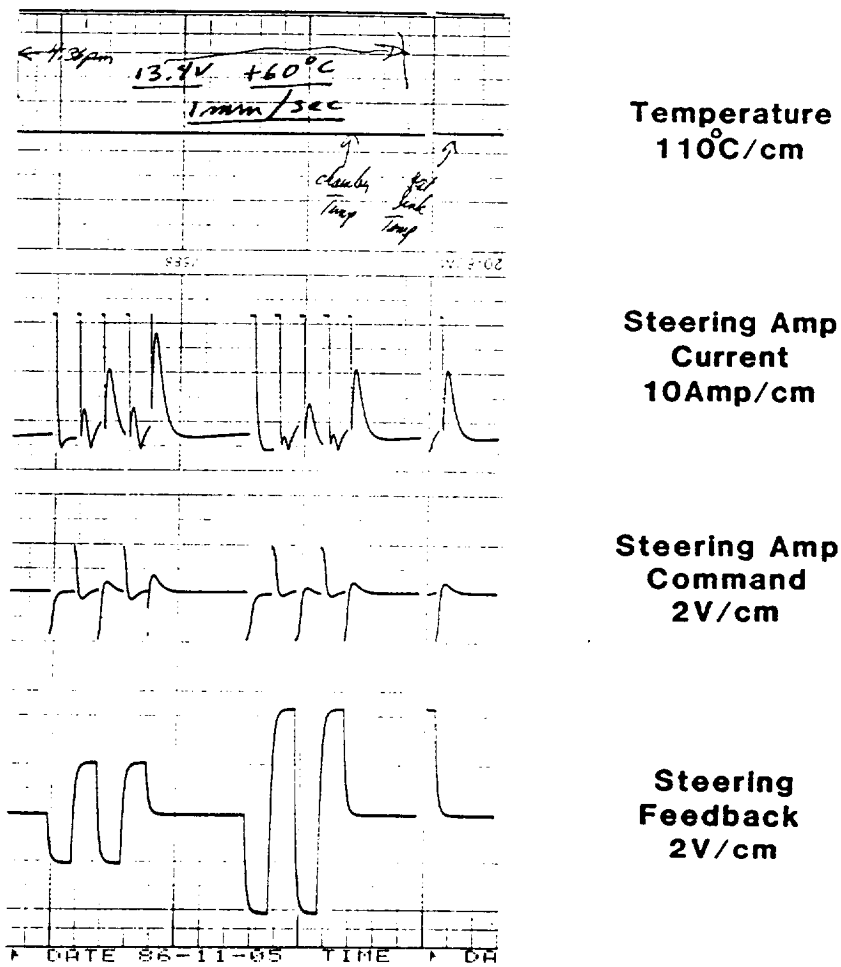


FIGURE C-164. STEERING SERVO TEMPERATURE SOAK (AFTER COMPONENT REPAIR)

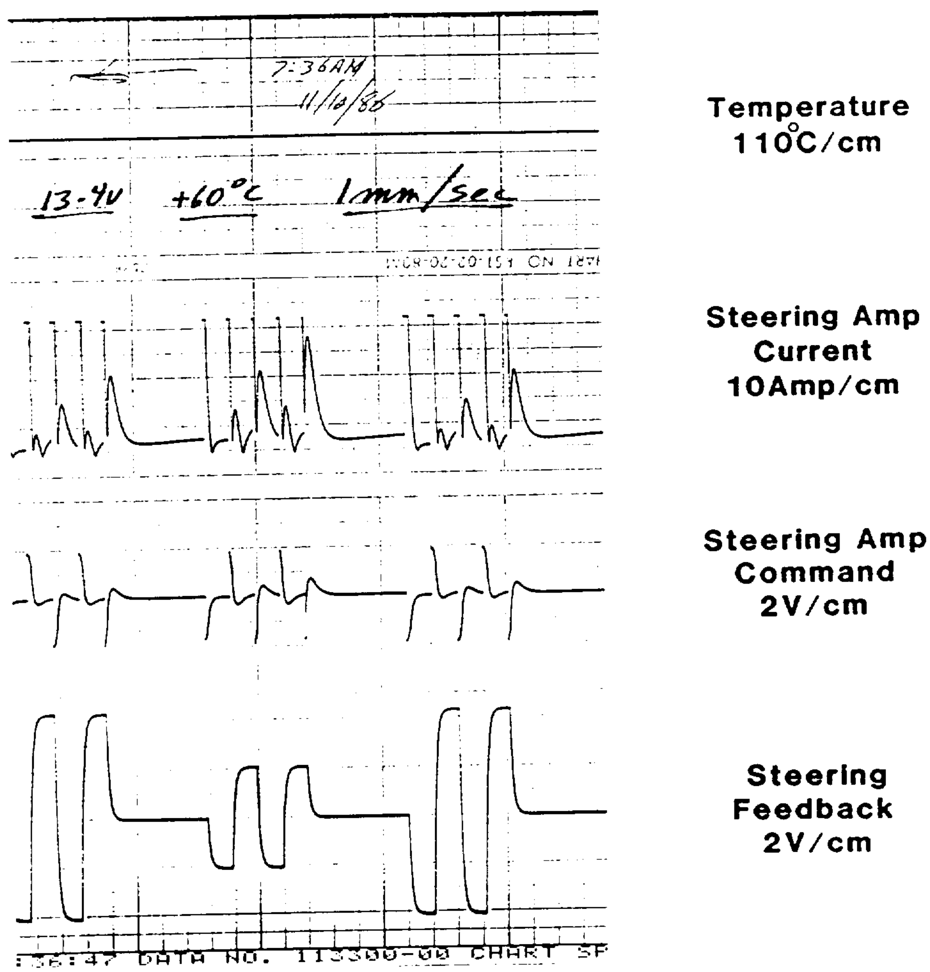


FIGURE C-165. STEERING SERVO TEMPERATURE SOAK (END OF 7 DAY TEST)

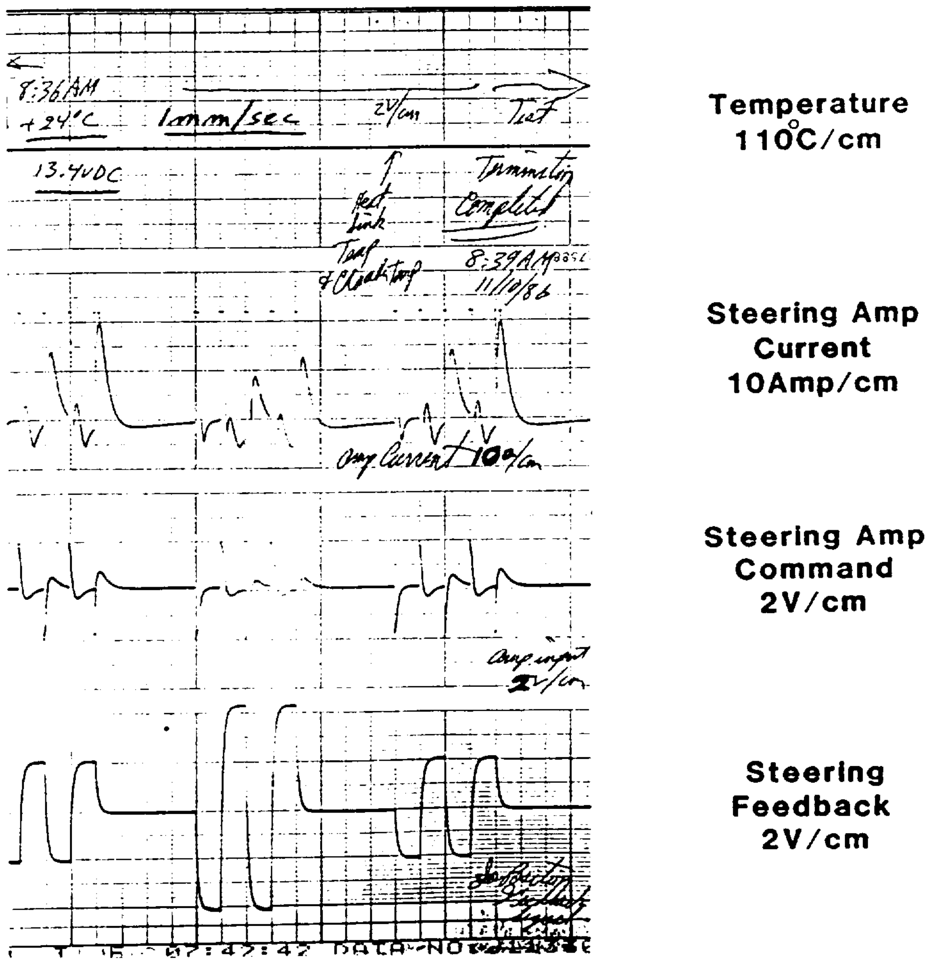


FIGURE C-166. STEERING SERVO TEMPERATURE SOAK (FINAL AT +24 C)